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Geophysical Methods for Determining Soil Thickness and Bedrock Configuration

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INTRODUCTION

This report contains recommendations as to the geophysical methods or combinations of methods best suited to determine the thickness of soil, configuration of the soil-bedrock interface, and the location of ground water concentrations for input into Levels II and III of a stability analysis for a landslide hazard evaluation system. Included are all interpretational techniques, computer programs with algorithms and documentation, geophysical results along all survey lines, and comparisons of geophysical interpretations with drill hole data at the ground monitoring sites. Equipment needed to perform the recommended geophysical methods are also discussed.

The results of this study will ultimately be used in the example application of the landslide hazard evaluation system. Due to the limited number of geologic environments investigated, this study does not constitute a definitive evaluation of the use of geophysical methods in landslide hazard evaluation. However, if the recommendations in this report are followed, a significant improvement in geophysical technology as practiced by the National Forest Service will be realized.

As explained in the Problem analysis for Problem No. 3, this study (Study No. 6) is part of an overall scheme to develop and test a three-level landslide hazard evaluation system. Geophysical investigation of the subsurface will be used to objectively determine values of soil thickness (d) to be entered into the landslide hazard evaluation system. The prime objective of Study No. 6 was to evaluate various geophysical methods for their ability to locate ground water concentrations and to determine depth to bedrock and the configuration of the soil-bedrock interface in the subsurface

conditions found in the National Forests of the northern Rocky Mountain Region (Hammond and Prellwitz, 1984).

This study was begun October 1, 1983, and was completed September 30, 1986. A detailed work plan for this study was written under a cooperative agreement with the University of Idaho by Sprenke (1984). The planned output for Problem 3, Study No. 6, Subproblem C, was set forth in Amendment No. 1 (22-C-4-INT-165) as follows:

1. Summary report of field tests to correlate geophysical interpretations of methods completed in FY 1983, FY 1984, FY 1985, and FY 1986 with drilling data.

2. Recommendations for improvement in geophysical field techniques and interpretational methods including computer algorithms and documentation.

3. Summary evaluation of geophysical methods with respect to landslide hazard evaluation.

These three items form the major portion of this report.

PART I: SCOPE

Introduction

The 1985 planned output for Problem 3 (14), Study #6, Subproblem C was set forth in Amendment #1 (22-C-4-INT-165) as follows:

1. Summary report correlating geophysical interpretations of methods completed. For purposes of Problem No. 3, landslides are classified into two broad categories depending on whether the slide mass is composed of soil or bedrock (Prellwitz, 1981). Work under Problem No. 3 was limited to developing a system to evaluate the potential hazard for failures confined to the soil mantle. Through a sensitivity evaluation of the infinite slope equation, Simons and others (1978) determined that all of the parameters needed for stability analysis, soil thickness and slope inclination have the greatest effects--these being nonlinear--on the analytical results. Values of slope inclination are readily available; values of soil thickness are not. Accordingly, Study No. 6 was directed at evaluating geophysical methods potentially useful for finding the depth to the soil-bedrock interface and the configuration of that interface. Because ground water concentrations also affect both landslide potential and geophysical measurements, the location of these concentrations was also considered a primary objective of this study.

Geophysical methods are desired because, compared to drilling, they offer speed, portability, and economy. Although the depth to the ground water table may be determined via geophysical techniques, the values of saturated soil thickness used in the stability analysis is determined by ground water response modeling as described in Study No. 5, Ground Water Concentration

(Prellwitz, 1981). However, the location of ground water concentrations with geophysics helps flag areas of potential instability.

In addition to evaluation of individual geophysical methods, a universal methodology for determining soil thickness, and for locating ground water concentrations was developed for entering these parameters into the landslide hazard evaluation system.

The three-level landslide evaluation system begins with a simplified stability analysis with input values based on the available forest resource inventory data and is suitable for a resource planning phase. The system progresses into more complex analysis and data input commensurate with the needs of the management activity. For each level of stability analysis, the mean and variance of soil thickness must be known or estimated from samples in order to assess the failure probability (Prellwitz, 1981). Because each level of stability analysis draws from a different data base, the values of soil thickness used will have different degrees of reliability as shown in Figure 1. The reliability of soil thickness used in Level I and II analysis should improve as data from Level II and Level II studies are fed back into the system.

The degree to which geophysical methods are utilized depends on the level of analysis. At the level I stage, no geophysics is typically involved. Estimates of soil thickness and location of ground water concentration are based on empirical correlations to landtype characteristics. Landtypes on the Clearwater National Forest, for example, are delineated on the basis of landform characteristics, vegetation, soils, and parent material (Wilson and others, 1984). While soil depths vary within a landtype, they occur in a

		Soil Thickness	
Level	Data Base	Derived from	Relative reliability
I	Resource Inventory	Empirical correlations of soil thickness to land type interpretations	Least
II	Timber Route Reconnaissance	Level I input, plus classification of of cutting units and route into similar segments based on limited geophysics.	Moderate
III	Critical Site Sampling	Level I and II input, plus extensive geophysics to extend drilling information.	Most

Figure 1. Table of reliability at the three levels of investigation.

predictable pattern that allows experienced forest specialists to subjectively estimate the mean and variance of soil thickness as well as the location of ground water concentrations.

In Level II analyses, geophysical methods are used to improve the estimates made at the Level I stage of soil thickness, configuration of the soil-bedrock interface, and locations of ground water concentrations on areas of proposed timber sale cutting units and road locations where potential failures are anticipated. Feedback of data into Level I analyses also improves general soil thickness estimates in similar areas. The data collected also proves useful for estimating road construction difficulty.

For Level III studies, geophysical methods are used to determine the subsurface profile at critical sites. When drilling is also performed, the two data sets combine to produce a very precise high-resolution picture of the subsurface environment.

OVERALL OBJECTIVES

The overall objectives of this study are to test and evaluate geophysical methods for determining soil thickness, configuration of the soil-bedrock interface, and locations of groundwater concentration, for use in stability analysis at levels II and II of the landslide hazard evaluation system. There are three main objectives of this study:

1. Conduct field tests of various geophysical methods.
2. Improvement of geophysical methods.
3. Evaluation of geophysical methods.

This report details the work completed from FY 1983 to FY 1986 toward the ultimate achievement of the above overall objectives. In particular, the correlation of data obtained during FY 1984 with borehole information at several study sites is discussed and several computer programs used in the interpretation of the geophysical data are described. This final completion report covers the entire four year project.

OBJECTIVE 1: FIELD TESTS

During FY 1983 through FY 1986, seven geophysical methods were evaluated to determine their response to the following parameters: soil thickness, shape of the soil-bedrock interface, and location of ground water concentrations. The seven methods included seismic refraction, seismic reflection, downhole seismic, ground penetrating radar, high resolution resistivity, spontaneous potential, and electromagnetic induction. These methods were initially selected because of their established potential for results in shallow soil environments. The field tests were performed on four sites in Region 1, two in granitic and metamorphic terrain on the Clearwater National Forest, one in carbonate terrain on the Nezperce National Forest, and one in basalt and metamorphic terrain also on the Nezperce National Forest. Control for the experiments was provided at three of the four sites by drill holes installed as part of Study 5--Groundwater Concentration. Additional boreholes were drilled at one site to verify seismic refraction results. Table 1 summarizes which methods were performed at which sites.

TABLE 1: SUMMARY OF FIELD TESTS PERFORMED

SITE	SEISMIC REFR	SEISMIC REFL	DOWNHOLE SEISMIC	RESIST	SP	EM	GPR
1. Dan Lee Ridge	FY83-84	FY85-86	FY84	FY84	FY84	FY84	FY84-85
2. Lean-To Ridge (North)	FY83						
3. Lean-To Ridge (South)	FY83	FY85-86	FY84	FY84			FY84-85
4. Kessler Creek							FY85
5. Grouse Creek							FY84

OBJECTIVE II: IMPROVEMENT OF GEOPHYSICAL METHODS

While several of the techniques tested are conventional tools used by geo-engineers, improvements in field procedures and interpretational techniques were found necessary to make the methods applicable to the shallow (<25 ft) but variable soil conditions typically found in the mountainous terrain of the National Forests. Some geophysical methods do not yield accurate ground water or bedrock depth information in specific geologic environments due to a lack of contrast in physical properties between the water, soil, and rock. Some methods are not applicable to shallow conditions in general. In particular, the generalized reciprocal method (GRM) of seismic refraction interpretation (Palmer, 1980) and resistivity pseudo-section profiling were scaled down from their usual applications to be useful for shallow soil investigations.

Emphasis was also placed on the implementation of geophysical interpretational programs on field microcomputers. Data interpretation in the field allows for enhanced quality control and better planning for additional work.

Integrating two or more geophysical techniques to improve overall geophysical site interpretation was also investigated. For example, resistivity work, along with seismic refraction data, has been found to be useful for the identification of altered and fractured zones in granites (Applegate and Donaldson, 1977). In general, the combination of several geophysical techniques was found to help differentiate

lithologic types and to increase the accuracy of geophysical interpretation.

Improvements in existing equipment and new equipment development was also investigated. Evaluation tests showed that improvements in existing geophysical equipment systems was necessary to make them effective and efficient in shallow soil environments.

OBJECTIVE III: EVALUATION OF GEOPHYSICAL METHODS

Conclusions were made as to the effectiveness of each method within the geological sites tested. Factors evaluated included:

1. Accuracy of soil depth, bedrock shape, and ground water location as compared with drill hole data.

2. Limitations of the method within the particular geologic environment. For example, ground-penetrating radar was not found to work well in basalt-derived soils; electromagnetic techniques were found to be unresponsive in granitic environments.

3. Ease of interpretation. Is special training required to use the method effectively? If so, how much?

4. Portability, and sturdiness.

TIME SCHEDULE AND COST ANALYSIS

Time estimates and a personnel and cost analysis for the last three years of this study, as amended from and labeled according to Problem No. 3 Analysis (Prellwitz, 1981), are shown in Figure 2 and Figure 3, respectively. The project was completed on schedule within the budget shown.

TABLE 1 - TIME ESTIMATES

Study 6 - Input Parameters: Soil thickness, d; Depth to ground water, dw	Months			Timing	
	Field	Office	Lab	Start	Finish
1. Develop detailed work plan		2		FY 84	FY 84
2. Evaluation tests				FY 84	FY 85
a. Seismic methods	1	2			
b. Electrical methods	1	2			
c. Electromagnetic methods (EM-31 only)	.5	1			
d. Radar	.5	.5			
3. Empirical correlation to landtype	1	1			
Reports		3		FY 84	FY 86

Figure 2. Time schedule for the last three years of this study.

TABLE 1 - TIME ESTIMATES

Study 6 - Input Parameters: Soil thickness, d; Depth to ground water, dw	Months			Timing	
	Field	Office	Lab	Start	Finish
1. Develop detailed work plan		2		FY 84	FY 84
2. Evaluation tests				FY 84	FY 85
a. Seismic methods	1	2			
b. Electrical methods	1	2			
c. Electromagnetic methods (EM-31 only)	.5	1			
d. Radar	.5	.5			
3. Empirical correlation to landtype	1	1			
Reports		3		FY 84	FY 86

Figure 2. Time schedule for the last three years of this study.

SAFETY AND HEALTH

All field surveys associated with this project were carried out in accordance with the R-1 Subsurface Investigation Safety Guide. No explosives were used in this study. Rich Kennedy on the Nezperce National Forest assisted with the surveys at Kessler Creek.

ACKNOWLEDGMENTS

Many graduate students in the Department of Geology and Geological Engineering at the University of Idaho were involved in this study. Literature reviews were conducted by Robert Butts and Will Hultman. Field assistance was provided by Gerald Slothower and Jeff DeFreest. Instrumentation development was carried out by W.R. Hammond and Gary Stevens. Ken Gordon, Master Technician, College of Mines and Earth Resources, provided technical support.

COOPERATION WITH OTHER UNITS

Geophysical expertise necessary for this study was provided through a cooperative agreement with the University of Idaho. The Rogue River NF, R-6, provided a Geonics-31 for evaluation.

TABLE 2 - PERSONNEL AND COST ANALYSIS - STUDY 6

	Personnel (months)				Cost (thousands)							
	UI CO-OP		FS		UI CO-OP			FS		Operating	PFT	Total
Fiscal Year	Geophy-sicists	Grad Stds	Geotech Eng	Geol Eng	Travel	Supplies	Salary & Overhead	Travel	Supplies	Comput Subtotal	Salary	Costs
1984	2	*6	2	4	4	12.5	14.1	4		30.7	16	46.7
1985	2	6	2	4	2.7	6.1	19.8	4		[illegible]	16	41.2
1986	1	2	1	1	1	1	5	0		6	5	11.
									Total	[illegible]	37	[illegible]

*2 students, full time for 2 months

1 student, ½ time for 8 months

(includes programing)

Figure 3. Cost estimates for this study.

PART II: METHODS AND RESULTS

LITERATURE REVIEW OF THE USE OF GEOPHYSICS IN LANDSLIDE STUDIES

The use of geophysical techniques in the investigation of slope movements has been documented in the literature since 1949. The following literature review is from Hultman (1988).

The earliest recorded landslide studies using geophysical techniques are by Yamada (1949) and Momose (1949). Neither Yamada's or Momose's paper is available for review, but their studies are briefly discussed by Takada (1968). Trantina (1962) performed electrical resistivity and seismic refraction surveys on two landslides in California. Electrical resistivity sounding surveys were performed with a Wenner array with electrode spacings ranging from 3 to 39 feet, increasing in 3 foot increments. Trantina calculated depths from the sounding surveys using the cumulative resistivity method developed by Moore (1945). The cumulative method is an arithmetic scale graph with cumulative resistivity plotted on the abscissa and electrode spacing plotted on the ordinate. Changes in slope along this cumulative curve represent changes in subsurface lithology or structure with depth. For depths less than 100 feet the depth of investigation is assumed to equal the electrode spacing. Trantina used a single trace seismograph with a 16 pound sledge hammer and steel plate source for the refraction survey. The surveys were one directional and the source was moved away from the single geophone in 10 foot increments to a maximum distance of 100 feet. The first study was performed on a landslide located near Oakland,California. The bedrock depths predicted with electrical

resistivity were within two feet of the depth measured in the borehole, however depth predictions to intermediate soil lithologies were not accurate. Bedrock depths predicted with seismic refraction underestimated the depth to bedrock by five to six feet. Trantina suggested that this lack of correlation of seismic refraction depths with measured borehole depths maybe attributed to an irregular bedrock surface.

Geophysical results obtained from the second landslide located near Vallejo, California showed better results. At this location, the landslide material is composed of a silty clay containing silt stone rock fragments overlying a siltstone bedrock. Movement was believed to have occurred at the interface between the two lithologies. Seismic refraction depth predictions to this lithology contact were within one to three feet of borehole measurements. Similarly, electrical resistivity depth predictions were within three feet of the borehole predictions. Although Trantina's work was not effective for locating intermediate soil lithologies, he did demonstrate that geophysical techniques provide reasonable depth estimates for the overburden-siltstone bedrock contact.

Takada (1968) used the electrical resistivity technique on several landslides in Japan to estimate water table and bedrock depth. Takada performed Wenner array profiling and sounding surveys along traverses oriented approximately parallel to the landslide axis. Although Takada originally was concerned with violating the assumptions of electrical resistivity surveying (i.e.laterally homogeneous soil and horizontal surfaces with depth separating zones of contrasting resistivities) he

ultimately decided that as long as a soil or rock layer of relatively higher resistivity existed with depth then the electrical resistivity method is applicable. Although Takada does not specifically identify the electrode spacings, it appears the used spacings of 2, 10, 20, and 30 meters. Takada predicted bedrock and water table depths from resistivity soundings but he does not identify his calculation method.

Takada found that landslide activity is concentrated in zones of low apparent resistivity. He suggests that soil zones having low apparent resistivities (less than 50 ohm-m) represent areas of abundant ground water and greater slope movement potential. Takada proposed that electrical resistivity sounding is an effective method to locate the boundaries to underground geologic structure. Although the bedrock depths determined with electrical resistivity generally exceeded the actual depths determined by drilling, he suggests that the method provides a reasonable estimate of bedrock depth. Takada recommends that the resistivity method be one of the first investigations performed on a landslide to assist the geologist place drill holes.

Carroll, Scott, and Lee (1972) worked in cooperation with other teams from the United States Geological Survey (USGS) as part of a multi-disciplined investigation of the Loveland Basin Landslide, Colorado. Carroll and others performed a seismic refraction study of the landslide using a twelve channel seismograph with an explosive charge source. Each explosive shot averaged five sticks of 40 percent gel dynamite at distances of 25, 50, and 100 feet from the ends of the geophone lines. Shot points were also located at the center of each line to obtain more information on the variation of the overburden velocities. Geophones

were spaced 25 feet apart along lines orientated both parallel and perpendicular to the landslide axis. Results were interpreted as a two layer system with an overburden (landslide material consisting of soil and disturbed incompetent bedrock) velocity ranging from 1,000 to 2,700 feet per second (fps). The overburden overlies a zone having a velocity ranging from 2,000 to 6,0000 fps which was interpreted as moderately competent but still unconsolidated bedrock. Seismic surveys in other portions of the landslide identified competent bedrock as having a velocity of 14,000 to 15,000 fps. Carroll and others interpreted the lower velocity medium (1,000-2,700 fps) as the landslide material. Although a subsurface profile was provided, the method used to map the surface of rupture contact was not identified. Carroll and others stated that the quality of the results obtained in this survey were hampered by an irregular bedrock surface, severe attenuation of high-frequency energy and weak first arrivals, and by abrupt velocity variations within the near surface overburden.

Moore (1972), also part of the USGS team investigating the Loveland Basin Landslide, used electrical resistivity sounding surveys along lines orientated parallel to the landslide axis. He used an expanding Wenner array with electrode spacings increasing in multiples of three feet to a maximum of 39 feet to estimate the depth to lithology contacts. Moore recommended not using empirical sounding curves in landslide investigations because ideal subsurface conditions upon which the curves are constructed are not applicable to landslide field conditions. He recommends using the cumulative resistivity curve that he developed in 1945. Low apparent resistivity values will flatten the slope of cumulative resistivity curve indicating a lithology or

structure change. Moore suggested that the electrical resistivity method is an excellent technique for estimating the depth to the surface or zone of rupture when the zone of sliding occurs within a saturated soil zone. The zone of sliding corresponded with a low resistivity zone at the Loveland Basin Landslide and therefore Moore felt that the electrical resistivity was the appropriate choice to estimate the depth to the surface of rupture.

Bogoslovsky and Ogilvy (1977) represents the most complete landslide investigation using geophysical techniques. These researchers recommended establishing a uniform grid over a landslide area and performing electrical resistivity soundings, seismic refraction, self potential, and temperature surveys at each grid node. In lieu of a grid system they recommended establishing at least three survey lines parallel to the landslide axis and several survey lines perpendicular to the landslide axis. Bogoslovsky and Ogilvy are the only authors to recommend extending the lines well past the lateral boundaries of the landslide to obtain apparent resistivity values for undisturbed material. The authors suggested that in situations where the subsurface of the landslide is irregular, then the empirical curves developed assuming constant conditions within each layer are not applicable.

Bogoslovsky and Ogilvy (1977) found that contouring apparent resistivity values identified zones of increased percent saturation within the landslide. However, they theorized that these areas of low apparent resistivity represented zones of water flow through the landslide mass. Bogoslovsky and Ogilvy recommended that the geophysical surveys be performed several times a year to determine the variations of

resistivity, self potential, temperature, and seismic velocity with time. Results indicated that seismic velocities changed very little with the season and therefore were not a valuable indicator of seasonal drying and wetting cycles in the subsurface. One study of a landslide in the Soviet Union revealed that the apparent resistivity of the material located above the shear zone changed significantly with time while the underlying apparent resistivity remained relatively constant. This seasonal variation of apparent resistivity proved to be a significant feature in locating the surface of rupture which was interpreted as contact between the differing resistivity zones. Bogoslovsky and Ogilvy recommend filtering the signals for both the seismic and electrical resistivity data. A specific filter was not recommended for the seismic signal, however, a 1 + cosine filter was suggested for the electrical resistivity data to remove all the high frequency noise. Bogoslovsky and Ogilvy also recommended the use of self potential and temperature surveys in landslide investigations. They believed that self potential contour maps reflected the pattern of the water table and subsurface lithology. Although the theory was not presented, they stated that self potential contours defined the spatial configuration, direction, and intensity of seepage flow. Temperature surveys were encouraged to supplement self-potential surveys in identifying the nature of subsurface water flow and soil saturation.

Cummings and Clark (1986) used a 12 channel enhanced signal seismograph with a 16-pound sledge hammer and steel plate source. Electrical resistivity surveys were performed along the same lines using a Wenner array. The electrode and geophone spacings were not identified. Geophysical results, later confirmed by drilling,

identified three layers; unsaturated landslide material, saturated landslide material, and unsaturated in-place bedrock. The depth of the contact between the landslide material and bedrock was found to be 95 feet. Although they support the use of geophysics in landslide investigations, they acknowledge that there are technical limitations to the method. Operational limitations include inadequate correction of field data, influence of surrounding man-made features, and large geophone and electrode spacings relative to the stratigraphy. Geological limitations include insufficient contrast of physical properties between layers, lateral heterogeneity of material, and layers having sufficient physical property contrast, but too thin to be detected.

FIELD TEST SITE DESCRIPTIONS

Site 1--Dan Lee Ridge

Site 1 is a 7.4 acre basin about 6 miles east of Pierce, Idaho. The site is located on the north side of Dan Lee Ridge about 1.5 miles east of Lost Hat Saddle on road 5173 on the Clearwater National Forest (SW1/4,NW1/4,Sec.14,T36N,R6E). The bedrock geology consists of a complex mix of border zone biotite gneiss and lesser quartz monzanite and related igneous rocks of the Idaho batholith (Hietanen, 1963). Thirty-six holes were drilled at the site in 1980 and 1981 for Study 5--Groundwater Concentration. The hole locations are shown in Figure 4. The holes were drilled by driving a split spoon sampler with a 130-pound drop hammer--the procedure for the Standard Penetrometer Test (SPT). This procedure yielded continuous core recovery so that the locations of the colluvial-residual soil contact and groundwater could be accurately determined.

Site 1 is covered by 0.0 to 1.2 feet of dark brown, organic top soil underlain by a 0.1 to 5.2 foot thick layer of red-brown silty fine-sand. This silty-sand has been identified as Mt. Mazama or Glacier Peak volcanic ash. Underlying the ash is a yellow-brown gravelly silty-sand which is colluvial soil derived from decomposed gneissic bedrock. The colluvium varies in thickness form 0.8 to 14.6 feet. A layer of residual soil less than 0.5 to 8+ feet thick typically underlies the colluvium, although residual soil was not encountered in all drill holes. The residual soil was distinguished from the colluvium by its saprolitic texture. The residual soil often grades into competent

Figure 4. Site 1--Dan Lee Ridge Contour Map

bedrock, but the depth at which bedrock was encountered varies sporadically from one drill hole to the next. Bedrock was "defined" as having a blowcount greater than 50 blows per foot. The layer of residual soil was not always completely penetrated. A grey-green fault gouge was encountered at a depth of 16-17 ft in drill holes 17 and 18.

Groundwater flow during the summer months is sparse. Some groundwater was encountered perched on the lowest spots on the colluvial-residual contact, and in fractures in the residual soil and bedrock. The largest groundwater flows occurred in drill holes 16 and 17, and in drill holes 35, 36, and 37. These flows appear to be controlled by faulting or bedrock fracturing. Figure 5 shows profiles through the drill holes.

Site 2--Lean-To Ridge North

Site 2 is located about 15 miles east of Pierce, Idaho on the north side of Lean-To Ridge, about one mile southwest of Savage Camp on Road 555.1 on the Clearwater National Forest (NW1/4,NW1/4,Sec.12,T36N,R7E). Twenty-five holes were drilled using the split spoon sampler during 1982 (Figure 6). Four tiers of holes span the major draw of the basin. The highest tier is 90 vertical feet below the ridge top and the lowest tier is 140 feet below the ridge top just above a spring.

The basin is blanketed by 0.2 to 1.5 ft of dark brown organic top soil, underlain in the draws or low spots by 0.5 to 3 feet of red brown silty fine-sand ash cap. The ash cap averages about 1.5 feet thick in the draws and thins to less than 0.5 feet on the ridges.

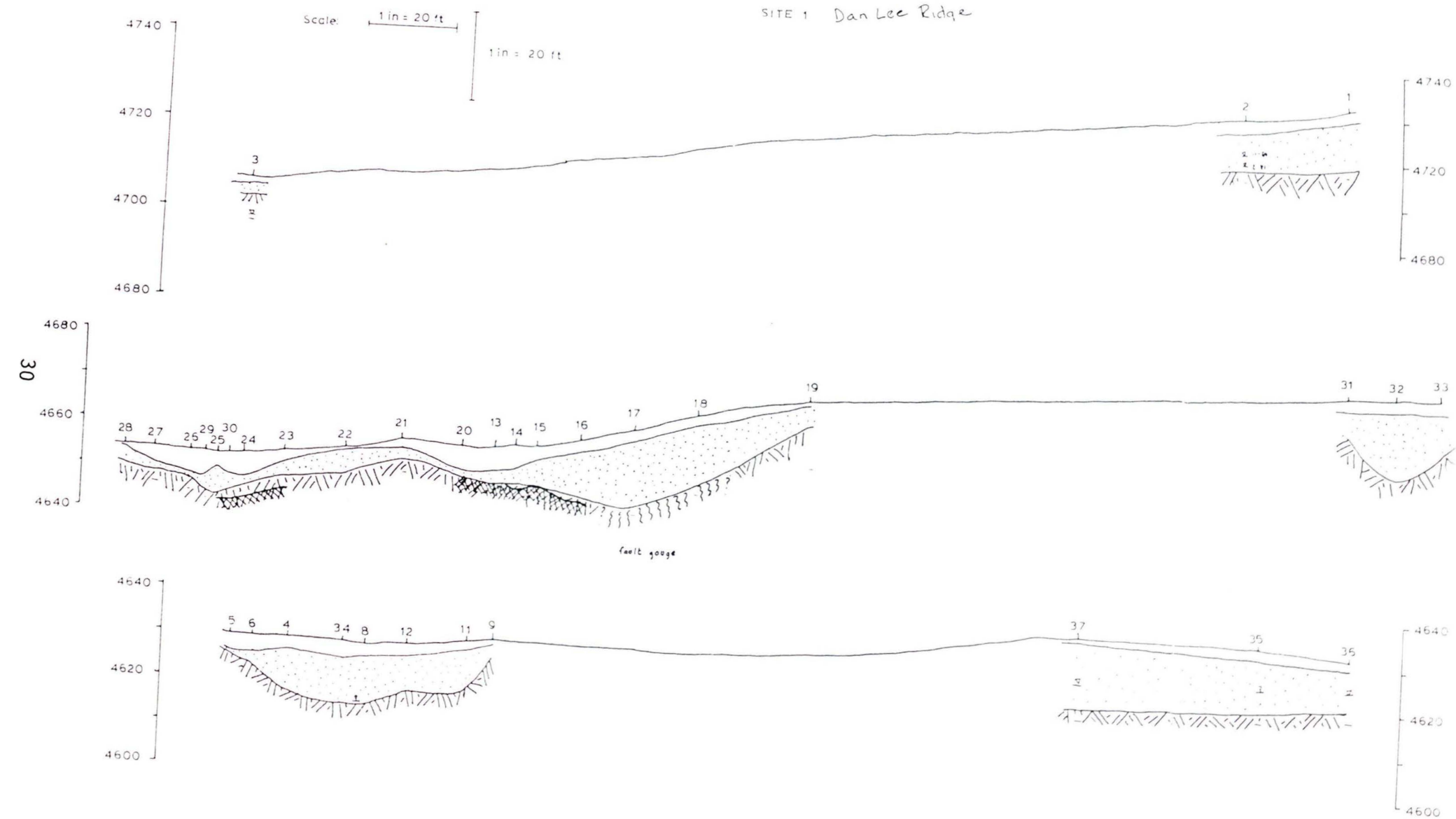


Figure 5. Site 1, Dan Lee Ridge Geological Sections.

Beneath the ash cap lies a light brown to brown colluvial silty sand. The colluvium is 0.5 to 1.7 feet thick in the uppermost tier and thickens to 2.8 to 5.2 feet in the lowermost tier. The colluvium also thins out of the draws toward the side ridges.

Granitic saprolitic residual soils with gneissic xenoliths underlies the colluvium. The colluvial-residual boundary is generally quite distinct based on both saprolitic texture. The residual soil is at least 1.3 to 4 feet thick in the upper two tiers. Only in drill hole 19 was the residual soil penetrated and bedrock encountered. In the third tier from the top, the residual soil is only 0.3 to 3.7 (ave. 1.5) feet thick., and is underlain by competent bedrock. In the lowest tier, bedrock was encountered sporadically. Bedrock is defined where blowcounts are greater than 50 bpf.

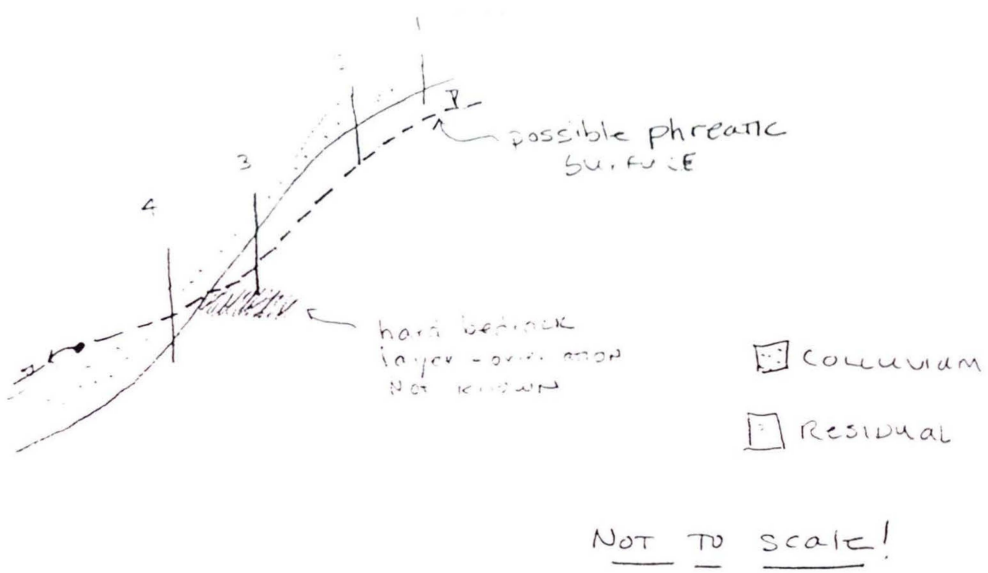


Figure 7. Conceptual groundwater model of Site 2, Lean To Ridge North.

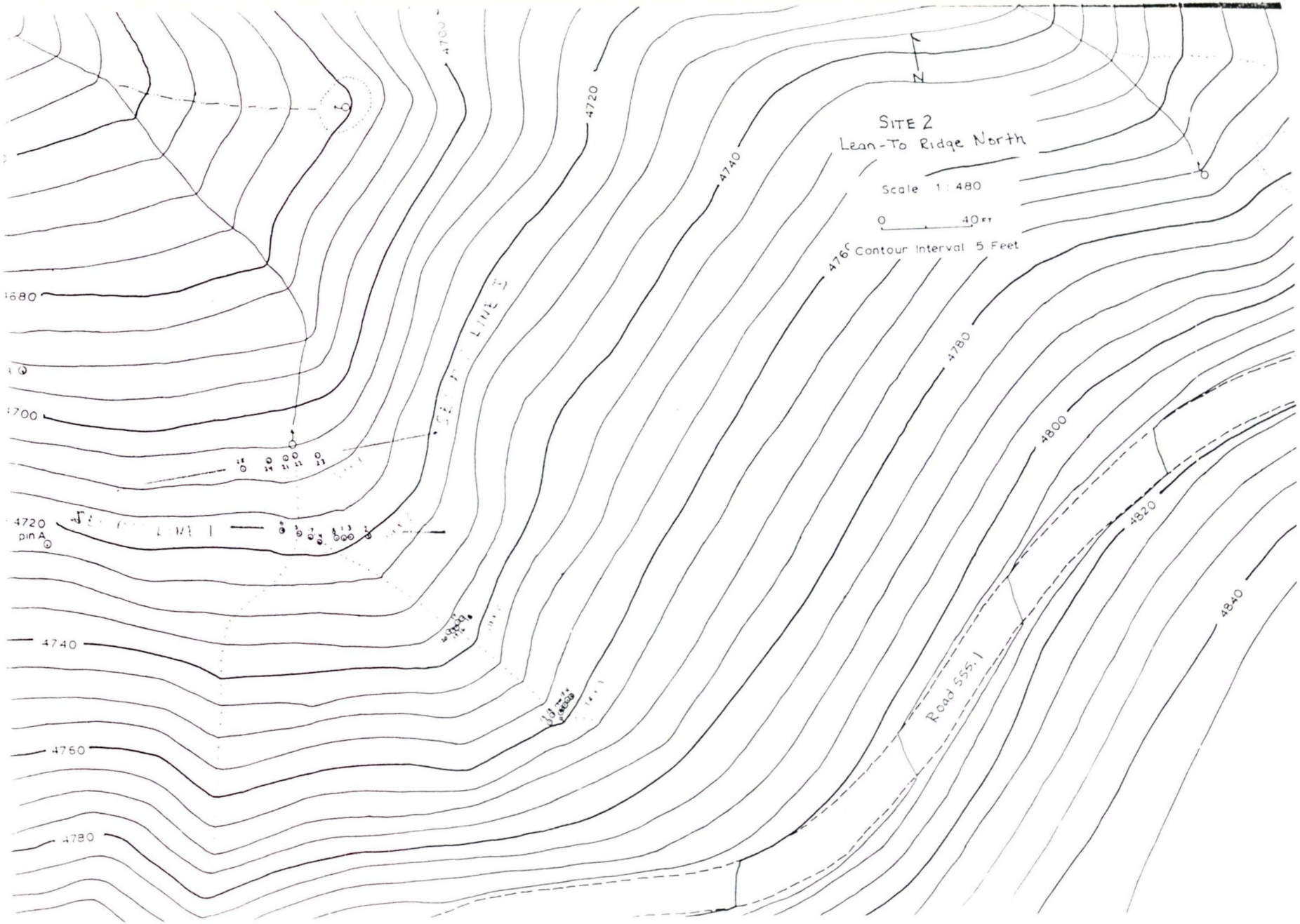


Figure 6. Site 2, Lean To Ridge North, Contour Map.

At the time of drilling, no ground water was encountered in the uppermost tier. Iron oxide stains near the colluvium-residual boundary in tier 2 indicates that ground water perches there intermittently. During drilling, the soils were saturated at the colluvium-residual contact in tier 3. Two weeks after drilling, however, the groundwater level dropped below the colluvium-residual contact, and was within 0.8 ft from one drill hole to the next. This might indicate an unconfined phreatic surface of water flowing in the fractures in the bedrock and residual soil (instead of water perched on the residual soil). In tier 4, the lowest tier just above the spring, ground water was encountered in the colluvium 3 to 4 feet below the ground surface during drilling. Sixteen days after drilling, during which time the weather had been hot and dry, the groundwater level had risen to within one foot of the ground surface, indicating the possibility of artesian flows within the fracture flow system. Figure 7 is a conceptual model illustrating the possible groundwater conditions at Site 2. Also in Tier 4, the groundwater profile exhibits a "hump" just above the spring. This might indicate a high flow source (bedrock fracture) between tier 3 and 4.

Site 3--Lean-To Ridge South

Site 3 is located about 500 feet east of Site 2 on the south side of Lean-To Ridge below Road 555.1 on the Clearwater National Forest (NE1/4,NW1/4,Sec.12,T36N,R7E). The bedrock geology is also primarily gneiss and quartz monzanite. Eight test holes were drilled across the basin using the split spoon sampler in 1982. The drill hole locations are shown in Figure 8. These holes showed that the site is covered by 0.2 to 0.8 feet of dark brown organic topsoil underlain by 0.8 to 1.8

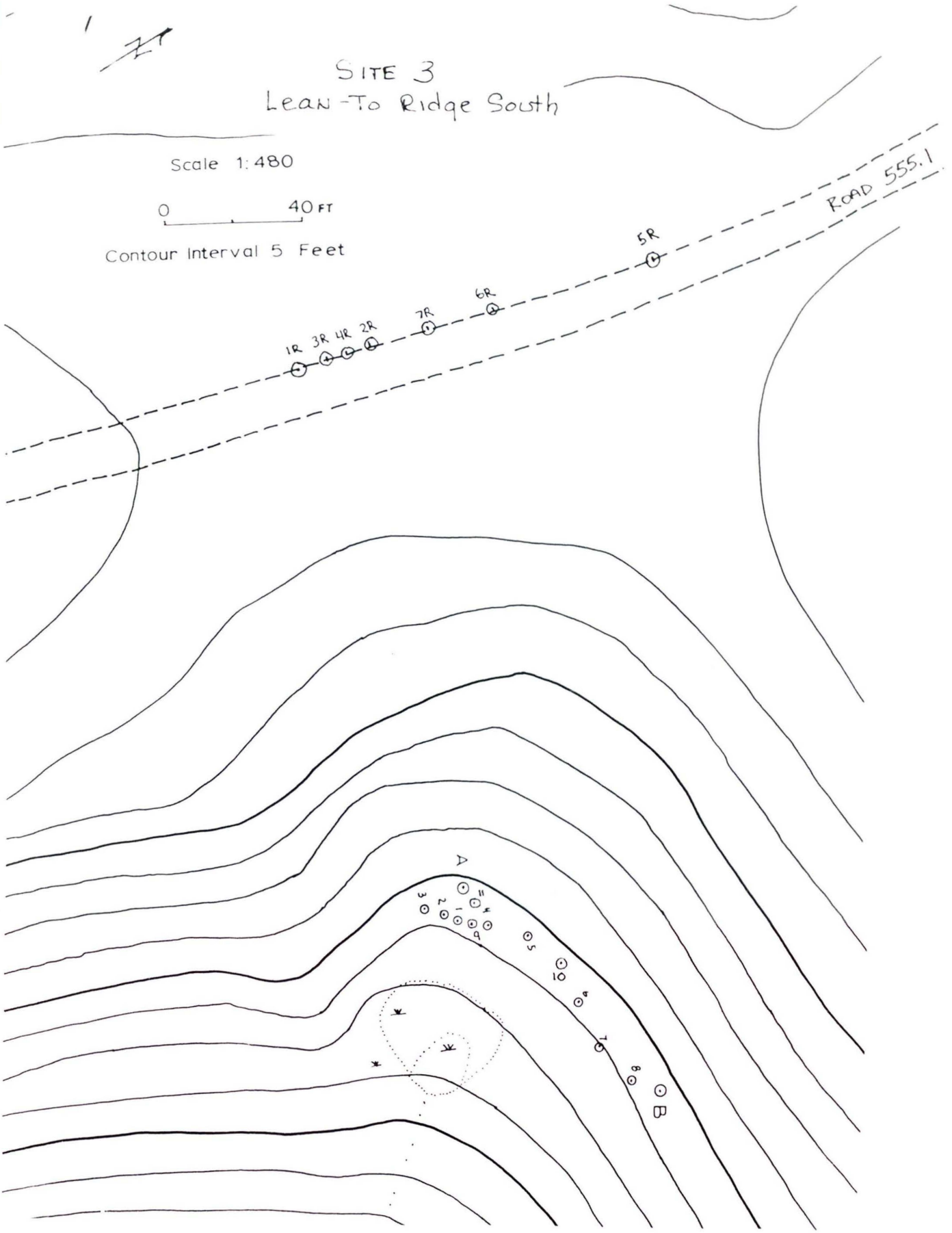


Figure 8. Site 3, Lean To Ridge South, Contour Map.

feet of red brown, silty fine-sand volcanic ash. Beneath the ash lies a 2.0 to 7.1 foot thick layer of brown silty sand interpreted as a colluvial soil. A tan to brown severely decomposed granitic residual soil underlies the colluvium. Drilling was stopped at 3 to 6 feet of penetration into the residual soil (for a maximum depth of 12 feet) even though bedrock (refusal) was not encountered. A cross-section through these holes is shown in Figure 9.

In 1984, two additional SPT holes (DH9 and 10 on Figure 9) were drilled in an attempt to locate competent bedrock to verify the results of seismic refraction surveys. These holes were inconclusive. In 1985, a Mobile B-53 caterpillar-mounted diamond core drill was used to drill a test hole to bedrock. This hole (#1) found competent bedrock at a depth from 15.8 to 16.2 feet.

In addition, seven holes were drilled using the core drill on the road at the ridge top to identify a reflector observed on ground penetrating radar records (DH R1 to R7, Figure 8). A polymer solution added to the drill fluid permitted nearly 100% recovery even in loose soil.

Groundwater was observed in drill holes 1,2,4,5,7,9,10, and 11 both perched on the colluvium-residual contact and flowing through fractures in the residual soil. The average depth to groundwater was 7 to 9 feet at the time of drilling (summer). Groundwater was not observed in the other holes, perhaps because they were not drilled deep enough to penetrate the water table.

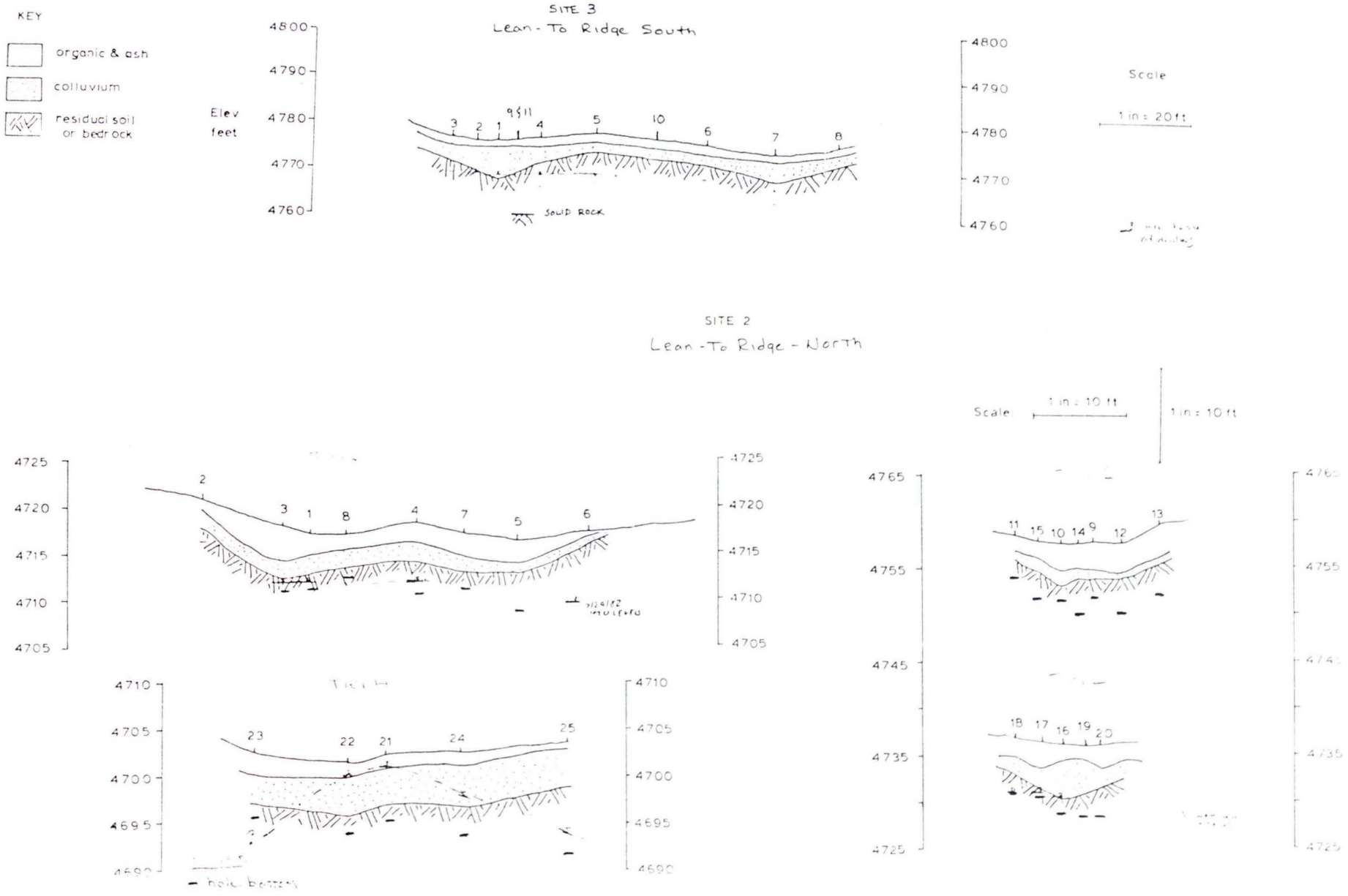


Figure 9. Geological Cross-Sections at Site 2 and Site 3.

Site 4--Kessler Creek

Site 4 is located 7 miles northwest of Riggins, Idaho on the Nezperce National Forest in carbonate terrain (NW1/4,Sec.26,T25N,R1W). Surface depressions along a proposed road location suggested the possibility of sinkholes or caverns. The site was not drilled, so geophysical interpretations could not be verified directly. However, comparisons were made between the three methods used at this site--seismic refraction, resistivity, and ground penetrating radar. Figure 10 shows a base map of the site showing the location of sinkholes, the geophysical survey lines, and the proposed road location.

Site 5--Grouse Creek Landslide

Site 5 is located approximately 17 miles southeast of Grangeville, Idaho along Forest Road 279 on the Nezperce National Forest (E1/2,Sec.32,T29N,R4E). The geology consists of approximately 20 to 40 feet of clay-rich basalt colluvium overlying a quartz-mica schist. The colluvium contains boulders up to 2 feet in diameter. Three holes were drilled at the site, DH1 by diamond core rig (1978?) and TPH2 and TPH5 by a split spoon sampler (1983). Figure 11 shows these drill hole locations. DH1 encountered the basalt colluvium and weathered schist contact at about 25 feet below the ground surface, and competent bedrock at a depth of about 35 feet. In 1983, slope movement ruptured the pipe in DH1 at 25.3 feet. TDH5 intersected the top of the weathered schist at 21 feet. Apparently, TPH2, also about 20 feet deep, did not intersect the schist. The ground water table was intercepted at about 4-7 feet in TPH2 and 11-13 feet in TPH5 during the summer. A

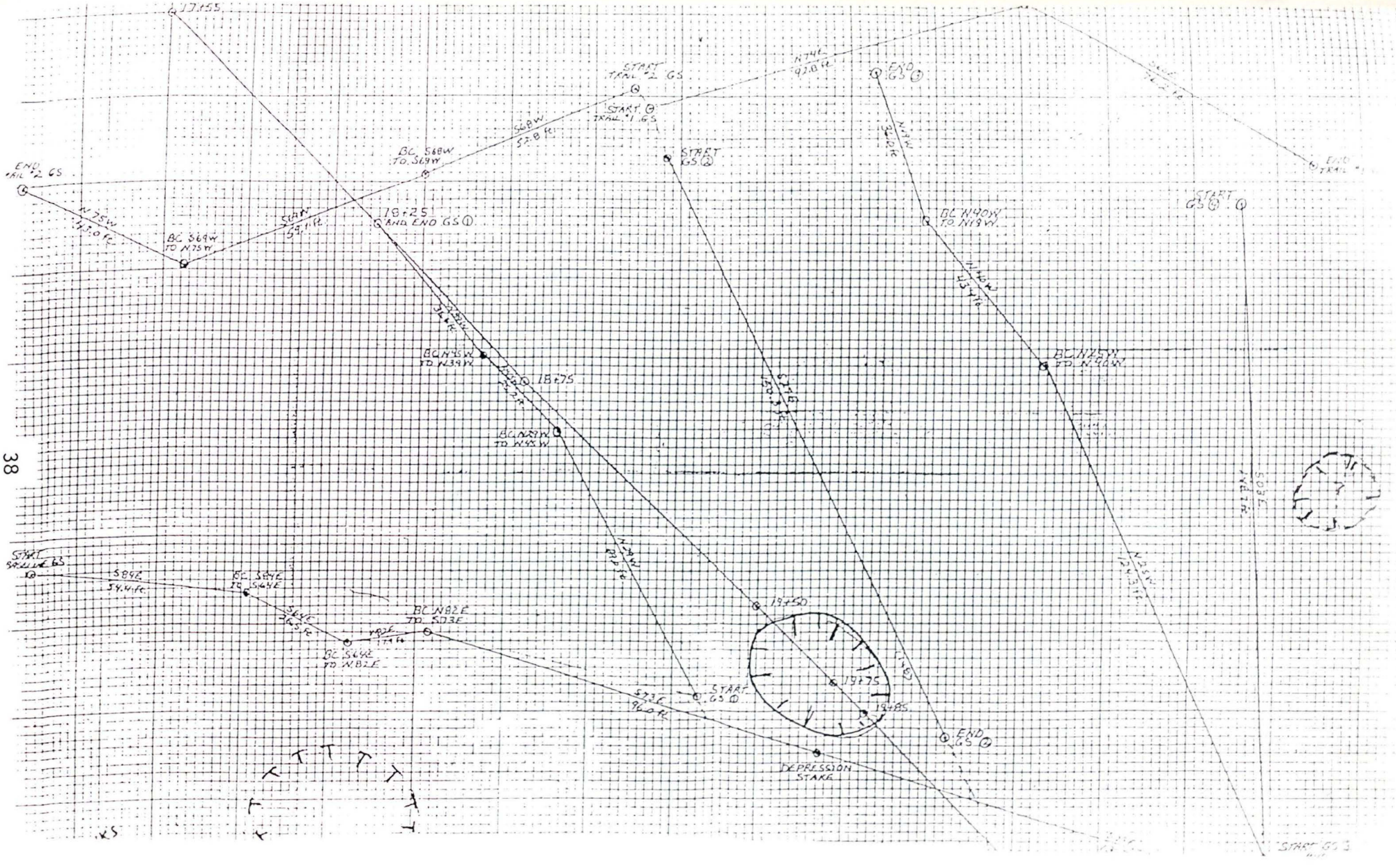


Figure 10. Site 4, Kessler Creek, Base Map showing the location of known sinkholes and the survey grid cut for geophysical measurements. The proposed forest road is also shown.

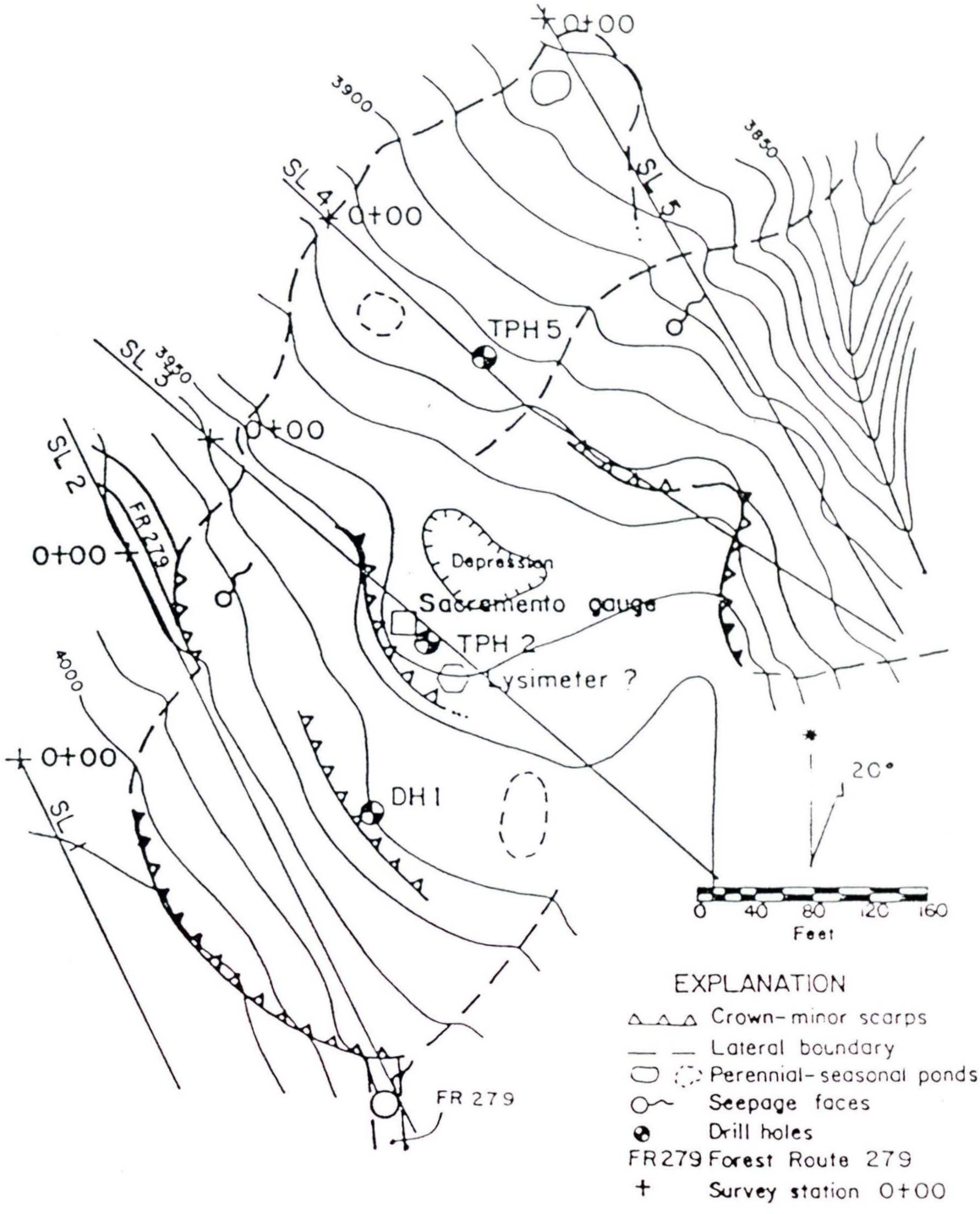


Figure 11. Site 5, Grouse Creek, Contour Map.

comprehensive geophysical and geotechnical study of this slide was completed by Hultman (1988).

SEISMIC REFRACTION

BASIC PRINCIPLES

Engineering seismic refraction surveys are used to determine the thickness of soils as well as the seismic velocities of soil and bedrock. Soil thicknesses are important in road construction, forest reclamation, and landslide hazard reduction. Seismic velocities can be related to soil moisture content, soil type, soil density, and bedrock rippability. General discussions of the engineering seismic refraction method may be found in Mooney (1980), The Forest Service Seismic Handbook, as well as in general geophysics texts such as Dobrin (1976) and Telford and others (1976).

The seismic refraction method of subsurface investigation involves the timing of artificially generated pulses of elastic energy as they travel from their source to a receiver--called a geophone. The geophone transforms the ground motion into an electric signal which is amplified and recorded on paper or magnetic tape. The source of elastic energy for shallow seismic work is typically a sledge hammer striking a metal plate although, for some situations, explosives are more effective.

The interpretational technique largely determines the field method to be used in regard to layout of geophones and shot-receiver distances. If more sophisticated techniques, such as the Generalized Reciprocal

Method (GRM) is to be applied, then very careful consideration must be given to the field technique in order that all the necessary data be collected in the field.

The seismic refraction technique is well known amongst geologists, civil engineers, and forest service personnel. However, very few of these people use the technique often. It is important that users of the technique have sufficient knowledge of the basic principles of the method in order to be able to judge if the method is applicable to a particular situation. Seismic refraction instrumentation today is largely the same as it was 40 years ago except that solid state circuitry has replaced vacuum tube amplifiers. The basic field methods and interpretational techniques have not changed greatly. Even sophisticated modern techniques, such as the GRM, are not fundamentally different from older techniques. They simply provide a framework within which a seismic analyst can work in an organized manner in the field and also obtain an interpretation in a similarly organized fashion.

Perhaps the major value of a technique such as the GRM lies in the fact that a similar field layout can be used in a host of different situations; nonetheless, judgment and imagination are still required to apply even such structured methods in the field. There are no unchangeable rigid ways to interpret seismic refraction data although the GRM does come closer than other methods in this regard; nor is the interpretation of the data any easier. Generally speaking, foreknowledge of site conditions and some comprehension of what makes sense from the geologic point of view always assists in interpreting the

field data into something meaningful, particularly for engineering purposes.

Perhaps the biggest problem with the seismic refraction method for engineering applications is the fact that engineers generally desire precise and accurate results just as might be obtained by drill holes. Seismic methods, by their very nature, carry an error of 10 to 20%. There is too much uncertainty in the velocities of geologic materials for results ever to be better than this accuracy. However, if some drill hole control is available, seismic refraction results can be calibrated to yield a fairly accurate picture of the subsurface between drill holes.

The seismic refraction method, as pointed out above, involves the measurement of seismic wave travel times. The source of the energy is generally a sledge hammer, weight drop, or small explosive. The instant of the shot is known as the time break. The shot generally triggers an oscilloscope which proceeds to capture the ensuing ground motion as detected by a geophone. At a certain distance from the source, called the critical distance, a seismic wave that refracts off higher velocity subsurface layers begins to arrive first at the geophones. This wave is called, for that reason, the "head" wave. The interpretation of these head waves is the basis of the seismic refraction method.

The general principle of a seismic refraction survey is illustrated in Figure 12. Usually, the energy source and the geophones are all located on the surface. Sometimes, explosive sources are placed in drill holes. However, for shallow investigative work, this is generally

not done because the upper layer is of great interest and it is not beneficial to have the source buried. Seismic energy propagates through the subsurface in much the same way that light travels through transparent media. Snell's Law governs the refraction angle of seismic waves as they encounter boundaries between layers of different seismic velocity.

The particular case of a seismic wave impinging on a boundary such that the wave is bent parallel to the interface is fundamental to seismic refraction. Perhaps the biggest and most serious limitation of the refraction method is the fact that the velocity of successive layers must increase with depth. If this is not the case, then it is not possible to detect the so called "low velocity layers." This is an uncertainty that is always present in refraction work. It is one of the reasons that a drill hole is so vital to the precise and accurate interpretation of seismic refraction data.

The distance at which refracted seismic waves begin to arrive before the direct wave from the source is called the critical distance. It is essential that a number of geophones be located beyond the critical distance in order that arrivals from deeper layers can be recorded. For engineering work, the deeper layer is generally bedrock, although in certain cases, it might be the water table.

True velocities of materials in the subsurface cannot be determined by a single shot and one line of geophones. It is always necessary to have a shot at both ends of a line of geophones. This allows computation of true, rather than apparent, velocities, and also allows

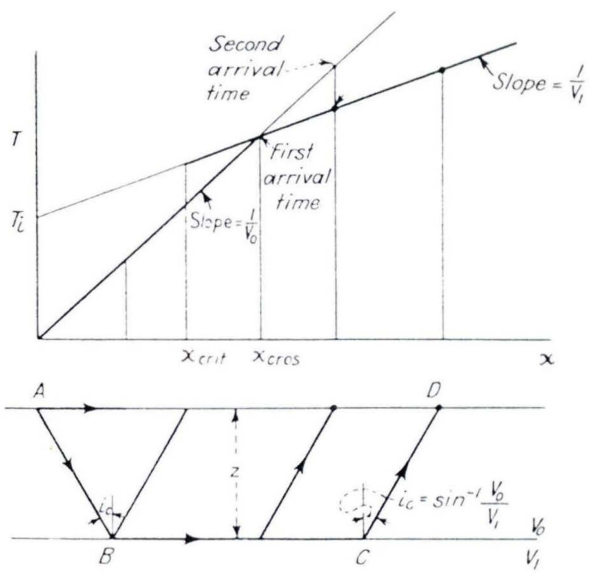


Figure 12. Typical seismic refraction survey.

determination of the depth to the refracting interface. However, even with such "reversed" shooting, complicated geological media can greatly confuse seismic records. These complications may include the presence of low velocity layers, a plethora of horizontal layers, and inhomogeneous layers. All these possibilities create complexities that an experienced user can often recognize. However, interpretation can be very difficult.

No geophysical method should ever be used without an appreciation of its limitations. Domzalski (1956) summarized many of the problems associated with shallow refraction surveys, and it is worthwhile to review these limitations here. A large portion of seismic surveys for engineering purposes are concerned with depths of less than a few tens of feet. At this scale, a single millisecond becomes an important unit of time and arrival times need to be measured to an accuracy of a millisecond or better. This requires that the elevations of the energy source and a; the geophones be known very accurately. Given an upper layer velocity of 1000 ft/s (typical of unsaturated soils), an error of a millisecond produces an error of one foot; given a velocity of 10,000 ft/s, a millisecond represents 10 feet of error. It is imperative that close control on the velocity of overburden be kept, particularly at locations where the overburden is not homogeneous. Unconsolidated overburden often shows large changes in elastic properties over relatively short distances. A large number of shots may be required to maintain adequate control on overburden velocity.

Irregularities in the shallow bedrock surface have a very pronounced affect when compared with deeper seismic surveys where

irregularities on the interfaces are generally ignored and the seismic data are usually interpreted in terms of planar beds. A highly irregular refractor surface will tend to make interpretational methods inaccurate because the times being compared represent different depths depending on the direction the shot is coming from and the location of the shot. The result is irregular travel times that differ in the forward and reverse directions as shown in Figure 13. Interpretation of these irregular curves can be improved by using the GRM.

Further problems arise is the surface is weathered as well as eroded. This is a very typical condition in the National Forests of Idaho where the bedrock-soil interface is a gradational boundary. Even with drill hole logs, it is not easy to see this interface. The top of the weathered bedrock surface may not be a good refractor whereas the top of the unweathered surface may be an excellent refractor.

Some materials may also be anisotropic. This could be encountered in the National Forests in gneissic zones in which the seismic velocity may be different along the foliations as opposed to across them. There may also be differences between horizontal and vertical velocities. Although these differences may be as large as 40%, differences of 10%-20% are more typical.

In interpreting seismic refraction data, there are no hard and fast rules to be followed when analyzing travel time curves. The interpreter must understand the expected shape of travel time curves over a variety of geologic media. Straightforward two or three layer plots with well-defined straight-line segments are the exception rather than the rule.

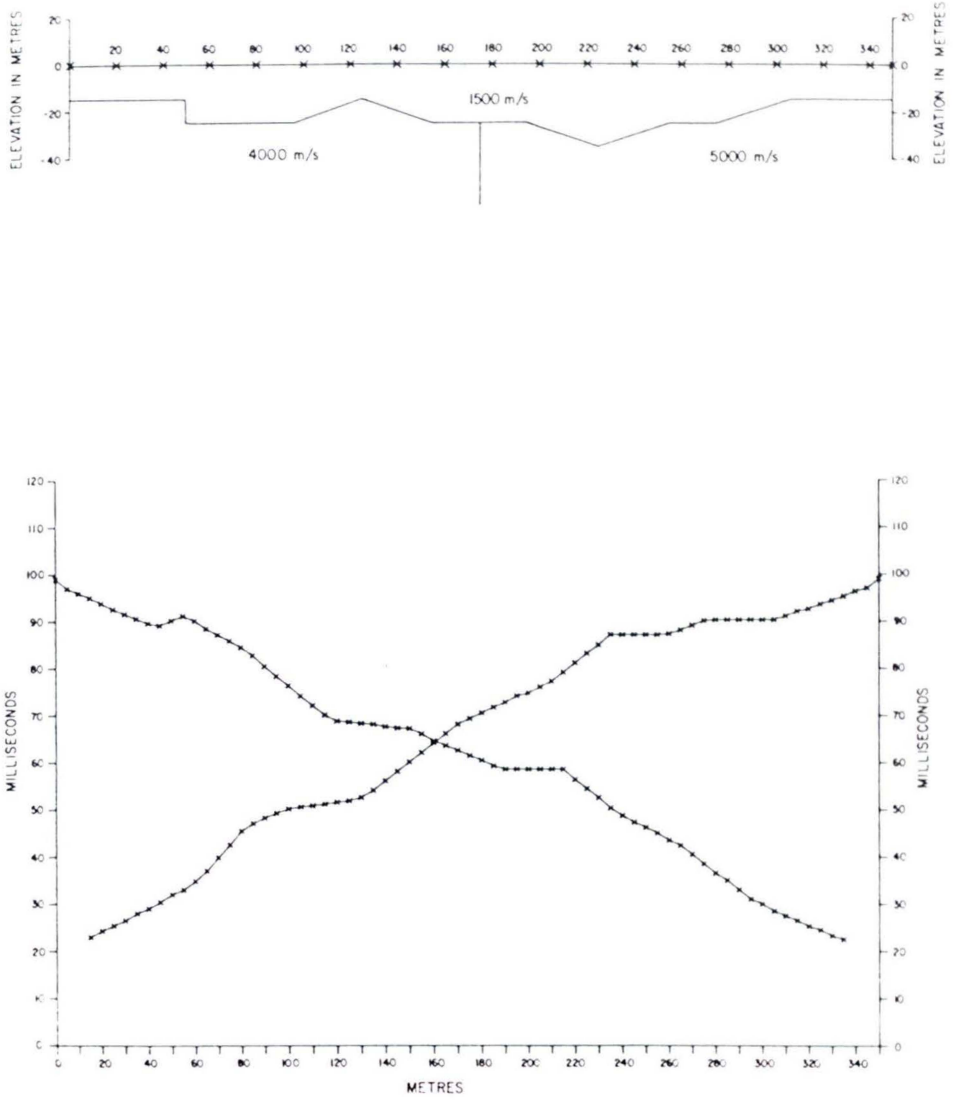


Figure 13. Effect of an irregular refracting surface on seismic refraction data.

Overburden velocities typically change along the length of the line, and generally, relief will be encountered on the bedrock surface. The first step in interpretation is to identify the layers present according to their seismic velocities and to determine which arrival times correspond to those layers. This is always the first step even with sophisticated methods such as the GRM. Some knowledge of site geology is essential for reconciling seismic interpretations with what is reasonable geologically.

Despite the above problems, the seismic refraction method is the most useful tool for shallow subsurface geophysical exploration. When refraction surveys are performed correctly, when interpretation is done with common sense, particularly in regard to potential geologic structures in the area, when some drill hole data are available, seismic refraction greatly speeds the recovery of subsurface information and can produce a very precise analysis of a site with minimal site investigation cost.

The Generalized Reciprocal Method (GRM)

During this project, a major thrust of refraction research was in the implementation of a sophisticated interpretational technique for the routine interpretation of seismic data at National Forest sites. A preliminary subset of this program is listed in the appendix. This particular program produces graphic outputs of the depth to bedrock using the reciprocal method and velocity estimates using best fit lines in a least-squares sense.

Many methods exist for the interpretation of seismic refraction data for engineering purposes. In particular, Forest Service personnel tend to use the intercept method as described in the Forest Service Handbook. This method is limited to planar soil-bedrock interfaces. Engineers also often resort to the plus-minus method, a technique that presumes very low dip on the soil-bedrock interface and a very high overburden-bedrock velocity contrast. Methods such as the above, though easy to implement, are unnecessarily simplified for state-of-the-art seismic refraction work---particularly with the advent of inexpensive readily available microcomputers.

The GRM involves few limiting assumptions and can be applied to conventionally recorded reversed refraction data. It is applicable to any shape of soil-bedrock interface, to interface dips as high as 20 degrees, and to any soil-bedrock velocity contrast. The methods also allows for the detection of hidden layers and improved estimates of overburden velocity--factors important for engineering investigations.

Because the GRM results in a profile of soil thicknesses rather than one estimate as with the intercept method, the GRM is particularly useful for probabilistic studies for which the variance of soil thickness in a particular soil type is an important parameter.

Bedrock Velocity Determination and the XY Factor

In conventional seismic refraction interpretation for which planar interfaces and uniform velocities are assumed, bedrock velocity is obtained by averaging the apparent head wave velocities on a

time-distance plot. Often, however, the soil-bedrock interface is irregular or the soil velocity may vary. In these cases, a better bedrock velocity estimate can be made by calculating a term Tm, called the minus term, for every possible pair of geophone locations separated by a distance XY (Figure 13), where XY can be as low as zero (as in the intercept method).

The minus term Tm is defined by:

$$Tm = (Tay - Tbx + Tab)/2$$

where Tay is the head wave travel time from shot A to y,
Tbx is the head wave travel time from shot B to x, and
Tab is the reciprocal time--the travel time from shot A to shot B, or vice-versa.

To determine bedrock velocity, values of the minus term Tm are plotted versus distance for a variety of possible XY values. The XY value for which the velocity curve is simplest (I.E. straightest or smoothest) is the optimum value. The velocity estimate of bedrock velocity, V2′, can then be determined by the inverse slope of the optimum plot (Figure 14).

An improved estimate of bedrock velocity, V2, can be determined if the approximate dip angle is known in advance of the survey. In this case:

$$V2 = V2' \cos (dip)$$

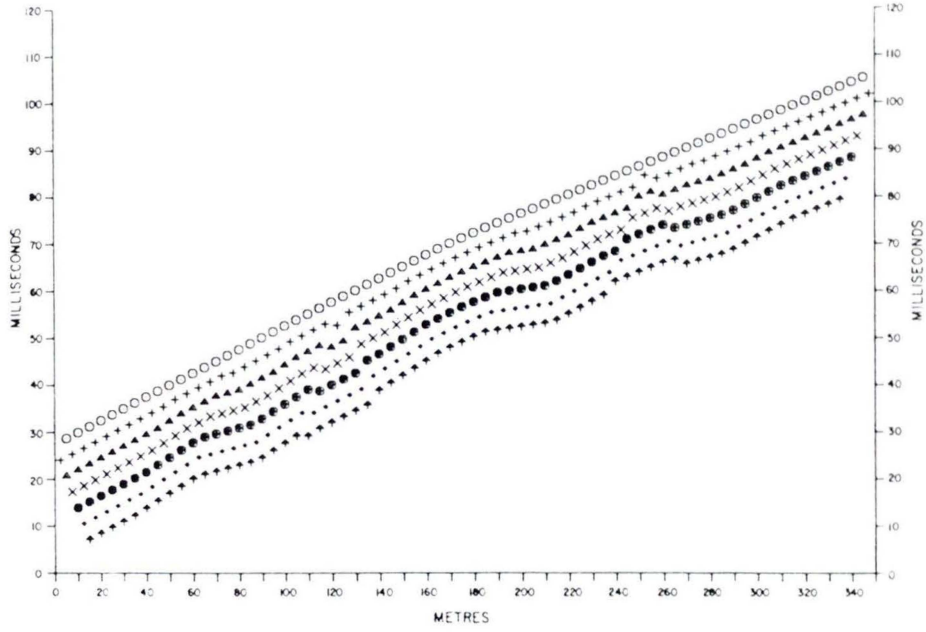


Figure 14. Velocity determination from the optimum plot using the GRM.

However, if the dip angle is not known apriori, the estimate V2′ is generally within 5% of the true value.

In some cases, the average soil thickness, soil velocity, and bedrock velocity are known in advance. The optimum XY value can then be calculated as follows:

$$XY = 2\ Z \tan(\text{critical angle})$$

where Z is the mean soil thickness. The critical angle can be estimated from:

$$\sin(\text{critical angle}) = V1/V2$$

The Plus Factor

After the bedrock velocity and optimum XY distance have been obtained, the plus factor, To, is calculated for each valid pair of geophones separated by the XY offset distance. This factor is then directly related to the depth to bedrock. The plus factor is defined by:

$$To = (Tay + Tbx - Tab - XY)/V2$$

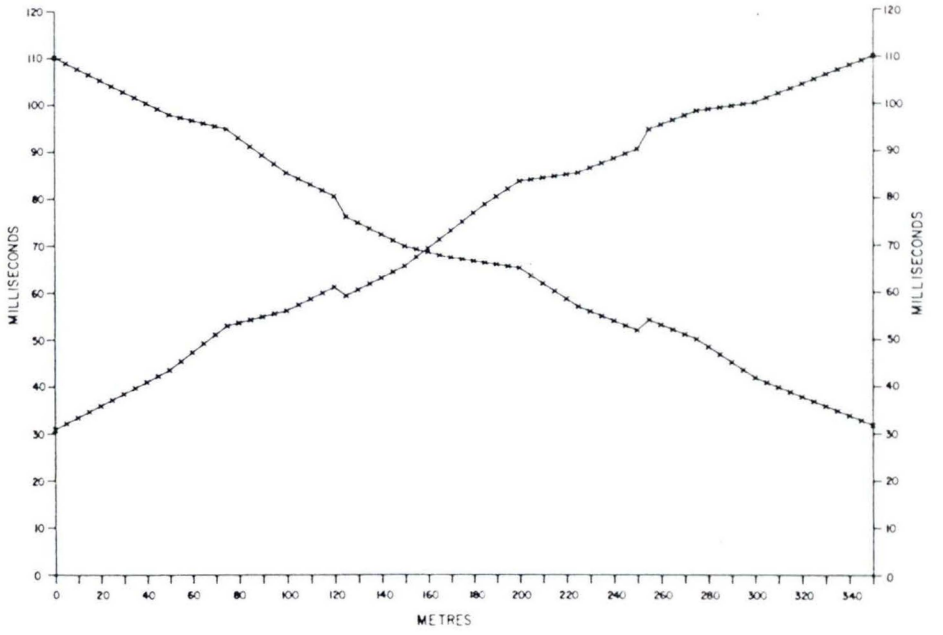


Figure 15. Example time-distance plot for the GRM.

If a new "velocity" is defined as:

$$Vo = V1 / [2 \cos (\text{critical angle})]$$

The perpendicular depth Z to the horizon is then:

$$Z = To\ Vo$$

The values are often plotted as arcs centered at a point G midway between the offset receiving geophones. The envelope of arcs from successive depth determinations along the profile then define the geometry of the subsurface refractor (Figure 16).

Alternatively, the location of subsurface refractor points can be determined using the standard equation for seismic migration in constant velocity media (Dobrin, 1976):

$$\text{Dip angle} = \{Z(n+1)-Z(n-1)\} / (2\ X\ )$$

where Z(n+1) and Z(n-1) are the computed perpendicular depths at horizontal offset locations G(n+1) and G(n-1) separated by a distance X from the offset location under consideration G(n). The computed dip angle can then be used to plot the subsurface point in its proper migrated position.

Field Technique

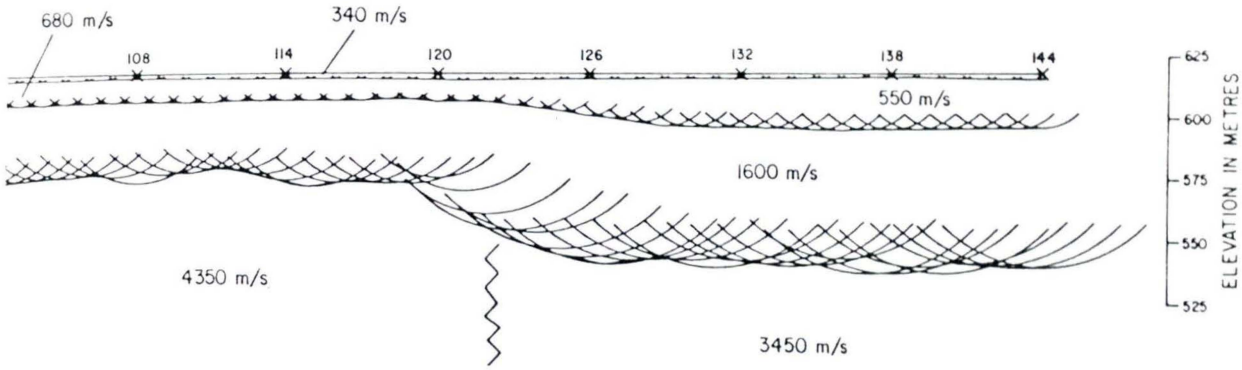


Figure 16. The envelope of arcs define the geometry of the subsurface refractor.

The general field procedures for conducting a seismic refraction survey particularly when using the GRM interpretational procedure are discussed below. The primary consideration is the interval to be used between the geophones. This spacing depends on the thickness of the upper layer and how much subsurface resolution is required. Generally, the total spread length should be about four times the maximum depth anticipated. Changes in geophone spacing can of course be made in response to the data observed. This requires that the operator be able to interpret the records as obtained in the field in at least a preliminary manner. There is actually no requirement that a constant geophone spacing be maintained on a seismic line. There is no reason why the phones cannot be placed at irregular intervals although this does add a certain degree of complexity at the interpretational stage.

Seismic cables generally come with fixed spacings between what are called the take-outs where the geophones may be connected to the cable. Though it is convenient to have a variety of cables with different take-out intervals, this is usually not the case. By far the most useful spacing for work in soil environments is of the order of 10 to 25 feet between geophones. The 50 to 100 ft spacings found on conventional cables are not suitable for engineering work.

The cable is usually laid on the ground in a straight line particularly if the GRM method is used. In hilly terrain, the elevations of shot and geophones must be determined for later corrections.

Outside shots need to be offset far enough from the ends of the cable to ensure head-wave arrivals at all phones if the GRM method is to provide bedrock information at all phone locations. Additional shots are also required at various other points along the geophone line in order to determine surficial layer velocity. It is important, when applying the GRM, to use shots at both ends of the line as well as distances more than one critical distance from the first phone. In general, at least four shots are required for each geophone layout; more shots can also be performed in the center of the line to obtain more information about top layer velocity. Top layer velocity is a critical parameter for shallow seismic refraction surveys. The recommended shot-receiver pattern is shown in Figure 17. The slight offsets shown of the shots perpendicular to the line are strictly a practical consideration to avoid damage by the blast or hammer to the geophones.

The most convenient source for shallow engineering work is a sledge hammer. However, to use this simple source, shot-receiver distances must typically be less than several hundred feet. At greater distances, explosive sources may be necessary. There are two disadvantages associated with explosive charges: a license is required and environmental statements are generally necessary. Small explosive amounts can produce large seismic effects in engineering work. A few ounces of commercial explosive is generally sufficient for lines as long as 300-400 ft. If explosives are used, seismic blasting caps with delays less than 1 ms should be used. Regular caps have delays as long as 15 ms. These caps can be employed only if a special geophone is placed near the shot to monitor the time break.

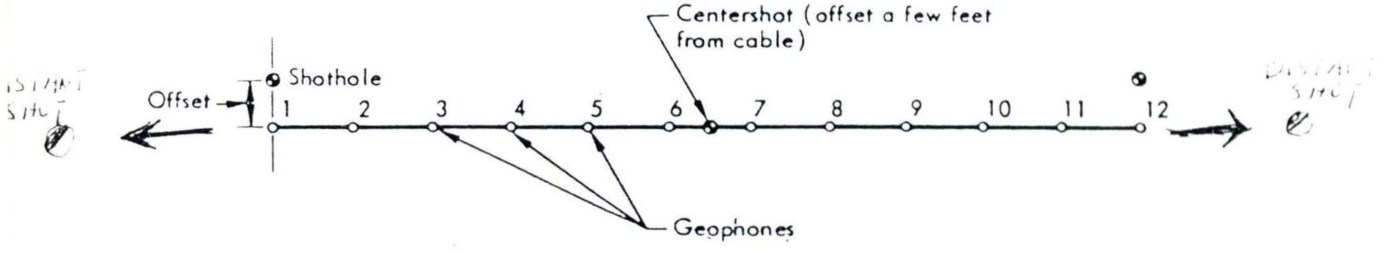


Figure 17. The recommended shot-receiver pattern for shallow refraction work.

Geophones must be firmly coupled to the ground. This is usually accomplished by attaching a spike to the phone. The spike can then be firmly implanted in the soil. In very windy situations, the geophones can be buried to reduce wind noise.

For engineering purposes, multichannel seismographs should be employed to improve field efficiency and interpretational ease. The price and weight of these units have dropped significantly in recent years. Multichannel units are now within the budget realm of engineering projects. They can be purchased for less then $10,000 or can be leased for less than $50 per day. Backpack units employing lightweight liquid-crystal diode screens have made multi-channel surveys far more practical for use in the back country than in the past.

Single channel units can be used. Although they have some advantage in portability, they have great disadvantages for data interpretation. It is very difficult to make adequate first-arrival picks when only one trace is available for inspection. It is very easy to confuse surface wave arrivals with first breaks, particularly in noisy conditions. There is always some judgment involved in picking first arrivals on a seismic record. A multichannel instrument allows the interpreter to exercise this judgment. If explosive sources are required, the number of shots required for a single-channel survey becomes prohibitive.

Refraction records for engineering work can generally be interpreted without time-consuming replotting of first arrival times if multichannel records are obtained (Figure 18). On the field records,

the locations of the shot and all geophones must be noted as well as the time scale of the record. The elevations of the shotpoints and geophones are generally tabulated in a separate field book.

After the first arrivals are picked, the direct wave on the record, if any, should be indicated with a sloping line through the origin (The record shown in Figure 18 does not show a direct wave). The velocity estimate V1 should be measured from the slope and indicated on the record. In addition, a sloping line should be drawn through the head wave arrivals for a first estimation of the velocity of bedrock. If possible, an estimate of reciprocal time should be made and noted on the record. Finally, the times of the headwave arrivals from distant shots should be transferred to the field book along with the velocity and reciprocal time information.

For GRM interpretation, two head wave arrivals--one from each end of the line--must be recorded at each geophone location. Because multichannel engineering seismic cables are 100′ to 600′ long, it is usually convenient to shoot long profiles in single cable length sections with shots sufficiently distant from the ends to ensure head wave arrivals at all phones. Additional shots are also taken along the cable to obtain direct wave velocity information. Long seismic refraction profiles generally involve a number of cable spreads, each of which records two or more shots. A large number of paper records are thus obtained during one field day. It is vital that the records and data are kept in an organized manner to facilitate processing.

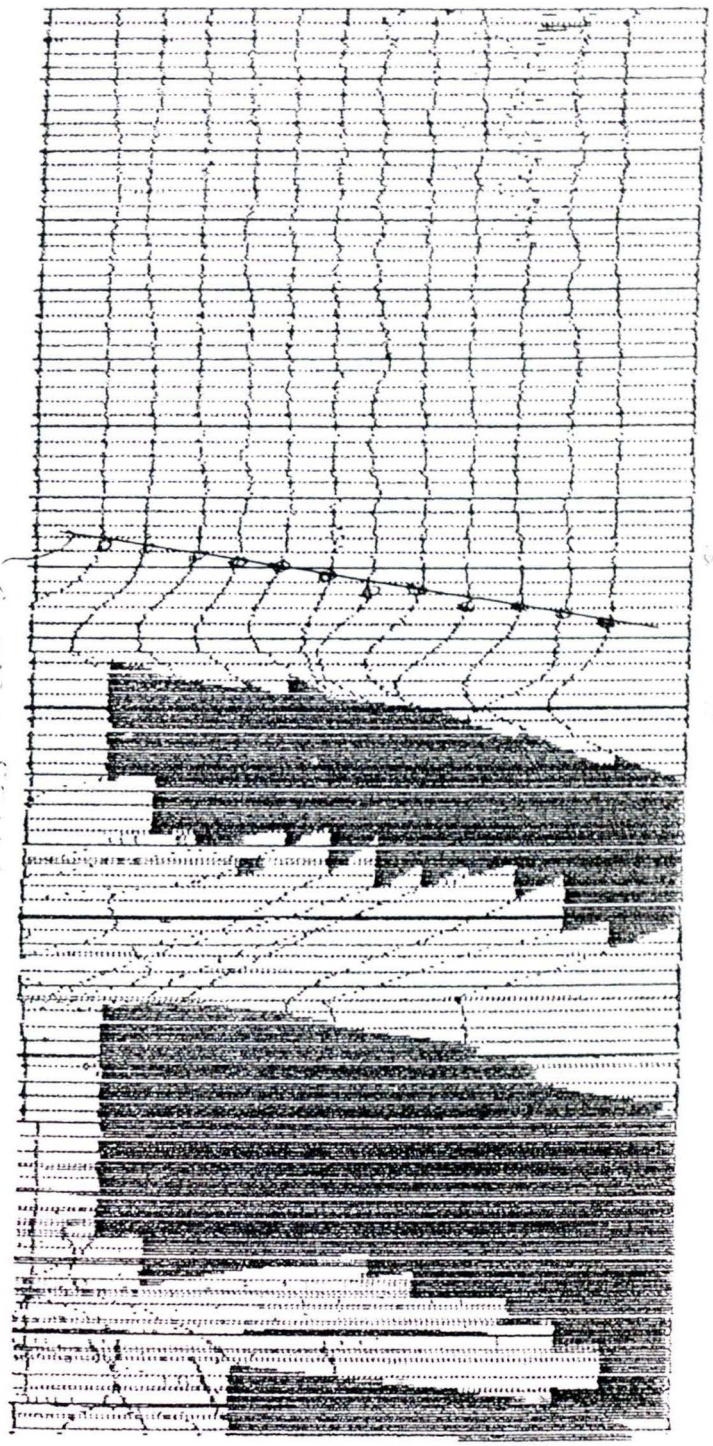


Figure 18. A typical multichannel seismic refraction record.

In summary, the GRM is a comprehensive technique to delineate undulating refractors using forward and reverse travel times. The head wave arrival times at two geophone positions, separated by a variable distance XY, are used for refractor velocity analysis and layer thickness calculations. For each set of geophones separated by distance XY, the "minus" term, Tm, is used to find V2, by plotting the values of Tm are plotted versus distance for a variety of possible XY values. The value of XY for which the velocity curve is smoothest is the optimum value. The inverse slope of the velocity curve for the optimum value of XY gives V2. Program SEIS13J, which is listed and documented in the appendix, performs all the analysis necessary for a GRM velocity determination. For each geophone pair, the "plus" term, To, is used along with the optimum XY and V2 from the velocity analysis and V1 from the direct arrivals to find the perpendicular thickness, Z, from the refracting point to the surface. The envelope of arcs from all the thickness determinations defines the geometry of the refractor. Program SEIS13K, which is listed in the appendix, carries out a complete GRM analysis and produces a fully migrated final depth section.

Intercept Method

Sometimes, the GRM is overkill. Many engineering sites are sufficiently simple to be analyzed in terms of a single refracting horizon using the "intercept" method. For the techniques below to apply, the bedrock surface must be planar. Each material present (overburden, bedrock) must be homogeneous and isotropic, and the seismic velocity in bedrock (V2) must be greater than the velocity of the overburden material (V1).

The angle of incidence at which a wave path is refracted parallel to the refracting interface is called the critical angle (Ic). This angle is related to the velocities by:

$$\sin(Ic) = V1/V2.$$

The velocities of the layers are found from the inverse slopes of straight lines drawn through the direct and head wave arrival times. The intercept of the best-fit line through the head wave arrivals with the arrival time axis is called the intercept time (ti). For the case of a single horizontal refractor, the thickness (z) of the upper layer is given by:

$$z = 0.5\ V1\ ti\ /\ \cos(ic)$$

Program SEIS13I, which is listed in the appendix, performs an automatic best-fit interpretation of single layer over a half-space refraction data. This program also provides a statistical analysis of the results including an estimate of the variance of the upper layer thickness.

Program SEIS13A, which is listed in the appendix, computes layer thicknesses and velocities for two horizontal layers on a half space given the intercept time, To, and one other distance-time point (X, Tx) for 3 events on a refraction profile.

Program SEIS13B, which is also listed in the appendix, interprets in-line seismic refraction data for the case of multiple dipping seismic

refractors. A number of seismic refractors of velocities, V(I), dip with dips, D(I), under an overburden of velocity, V(1). Shots are fired at both ends, A and B, of an in-line array of geophones, and apparent velocities, VA(I), VB(I), and zero-intercept times, TA(I), TB(I), are measured on the resulting travel time graph. The program finds true velocities, V(I), and dips, D(I), and vertical depths, DA(I), DB(I), below shots A and B. Dips from shot A toward shot B are considered positive. The algorithm used involves the following assumptions: homogeneous and isotropic layers, planar boundaries, increasing velocity with deeper layers. In practice, depths and velocities estimated by seismic refraction surveys are accurate to 10-20% provided that low velocity layers are not present. The dips calculated are apparent dips along the geophone line. This program, as written, can accommodate up to nine layers over a halfspace. Further information on the algorithm used can be found in Mooney (1980).

Program SEIS13C in the appendix calculates multi-layer refraction travel time curves. Functions are provided to calculate apparent velocities, time intercepts, and critical distances (where a break in the slope on a travel time curve occurs) so as to aid a geophysicist designing a refraction seismic survey. Low velocity layers may be included in the model. This program and documentation are based on Campbell (MGHCP, 1981). The program can handle up to 9 layers over a halfspace. The assumptions are constant velocity in each layer and planar boundaries between layers. The dips entered are positive down from the horizontal in a direction from shot A toward shot B. The dips are apparent dips in the direction of the geophone line. The program cannot handle pinchouts of layers beneath the geophone line. For

further information on the use of this type of analysis, see Mooney (1980).

Program SEIS13D computes elevation corrections for shallow seismic refraction surveys. Arrival times in seismic refraction surveys are influenced by the seismic velocities of the earth materials, the acoustic impedance, contrast between these materials, and the locations of the geophones with respect to the shotpoint. Commonly, the shotpoint is at a different elevation from the geophones, and the geophones are at different elevations from one another. The differences in elevation can lead to time-distance curves that are not representative of the subsurface conditions especially in shallow seismic refraction surveys. The accuracy of the interpretation can be improved by correcting the shotpoint and geophone elevations to a common datum below the surface but above the interface between the upper two layers. The equations used in the program are from Dobrin (1976).

Program SEIS13E in the appendix computes a combined elevation and weathered layer correction for shallow seismic refraction surveys. The equation used in this program is for the case where the shotpoint is located below the weathered layer. The equation used and an explanatory diagram are shown in the documentation. The equation is modified from Dobrin (1976)

The Plus-Minus Method

In some cases, the velocity of the soil mantle is much less than the velocity of bedrock, and a simple interpretation procedure, the

"plus-minus" method can be used. Program SEIS13F in the appendix calculates the depth to an irregular interface for shallow seismic refraction surveys. Engineering site investigations commonly require the depth to bedrock. Generally, the bedrock surface is overlain by weathered, residual soil, or dry and saturated alluvium. The bedrock surface is commonly irregular. Seismic refraction surveys can be used to investigate the bedrock surface. The "plus-minus" method is a quick and convenient method of interpretation. It is based on a wavefront approach.

The plus-minus technique used in the program is fully described in Cummings (Determination of depths to an irregular interface in shallow seismic refraction surveys using a pocket calculator, 1979, Geophysics, 44, 12, 1987- 1988) and Hagadoorn (The plus-minus method of interpreting seismic refraction sections: Geophysical Prospecting, 7, 158-181).

Hidden Layer Problems

Geologic conditions exist which produce hidden layers with respect to seismic refraction surveys. The significance for identifying a hidden layer in engineering geophysics is that it may represent, for example, a zone of weaker material such as a bentonitic layer sandwiched between an overlying sandstone and an underlying limestone. The weaker material may be a potential slip plane in a landslide.

Two major errors are introduced in interpreting the time-distance graph when a low-velocity hidden layer exists. The first is the

non-detection of the layer because it does not show on a time-distance curve. The second is the incorrect interpretation of the depth to the interface underlying the low-velocity layer. The data from the time-distance graph would result in a depth deeper than the true depth.

Program SEIS13G in the appendix handles the special case where a layer has a lower velocity than the layer above it and a higher velocity than the layer below. The lowermost layer must have the highest velocity of the three. Because the low-velocity layer refracts the seismic wave toward the normal, a head wave is not generated at the upper surface of the low-velocity layer. The head wave from the third layer will nonetheless exist. Consequently, the existence of the low-velocity layer is not apparent on a refraction record. However, under certain circumstances, its presence may be identified by time delays on a refraction record between the slopes for the underlying and overlying layers. Program SEIS13G in the appendix determines the possible thicknesses of a low velocity layer given the velocities of the materials present.

Even if it is not a low-velocity layer, a subsurface layer may also fail to show up as a first arrival if the critical distance for an underlying layer is less. In this situation, the head wave from the deeper layer arrives at the geophone earlier than the arrivals from the undetected layer. Program SEIS13H computes the maximum possible thickness of a hidden layer at a site given the observed crossover distance, the observed intercept time, the velocity of the substratum, and the velocity and thickness of the overlying layer. The equations are from Hawkins and Maggs (Nomograms for determining maximum errors and

limiting conditions in a seismic refraction survey with a blind zone problem, 1961, Geophysical Prospecting, 9, 526-532). For program SEIS13H, the velocity of the undetected layer is assumed to be higher than the overlying layer but lower than the underlying layer. Thus, the usual assumption of increasing layer velocity with depth is maintained from layer to layer.

FIELD TEST RESULTS

Site 1

A refraction survey was run along the seismic line shown in Figure 19 at Site 1. This line actually consisted of four separate geophone layouts, with the last geophone of each overlapping the first geophone of the next layout. The raw head wave arrivals collected are shown in Figure 20. After tying the results from all four layouts together by taking advantage of the overlapping geophone, the corrected head wave travel times are shown in Figure 21. The data in Figure 21 also includes time corrections for the bend in the seismic line (Figure 19).

A velocity analysis of the data from Site 1 is shown in Figure 22. This analysis was produced by Program SEIS13J in the appendix. The optimum XY distance is 0 feet as can be seen from the graph of the minus terms which become progressively rougher for higher values of XY and by the computer output which shows higher % error and variance in the best fit line to the minus terms. The best value for bedrock velocity was found to be 6242 ft/s.

The overburden velocity at the site was estimated from the direct wave arrivals for 12 shots along the line. The mean value of V1 was found to be 1170 ft/s. This value is typical of unsaturated sediments.

The refraction results for Site 1 are shown in Figure 23. The GRM bedrock estimates were made using Program SEIS13K in the appendix. Also shown are depth estimates using the intercept method with shots at 0 ft, 40 ft, 80 ft, and 120 ft along the line. The GRM results show a great deal more detail than the intercept results which require an assumption about a planar bedrock surface. Although the average depths determined by the intercept method generally agree with the GRM depths, the intercept results fail to detect the prominent bedrock channel on the left side of the line.

A comparison of the GRM bedrock with the geology of the site as known from the test holes (Figure 24) is enigmatic. On the left side of the line, the seismic bedrock surface is typically 10 feet deeper than the residual soil surface. However, the channel in the residual soil surface appears to extend down to the seismic bedrock surface. On the right side of the line, the seismic bedrock surface actually climbs above the residual soil surface, and the channel in the residual soil surface does not appear at all in the seismic results.

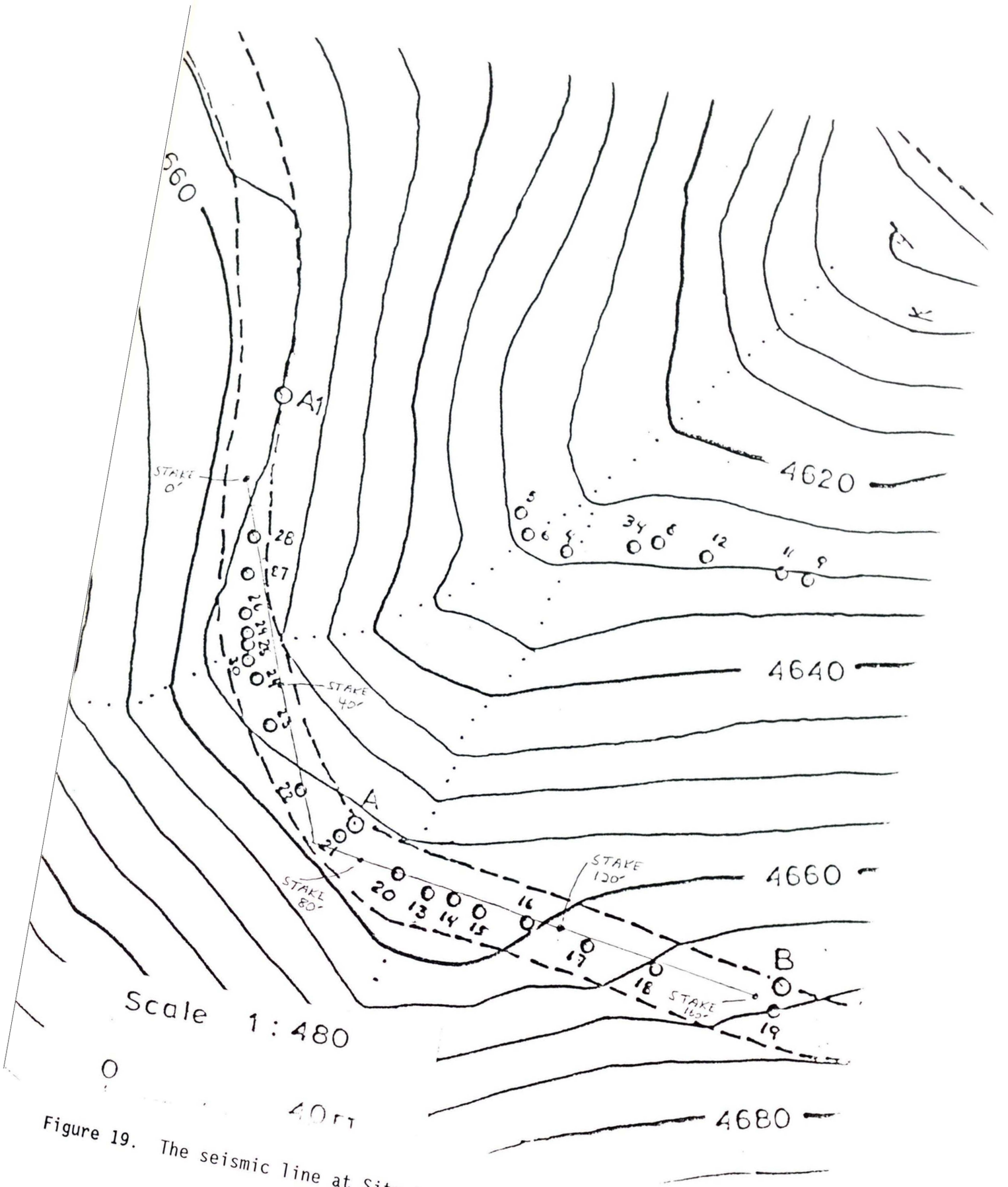


Figure 19. The seismic line at Site 1.

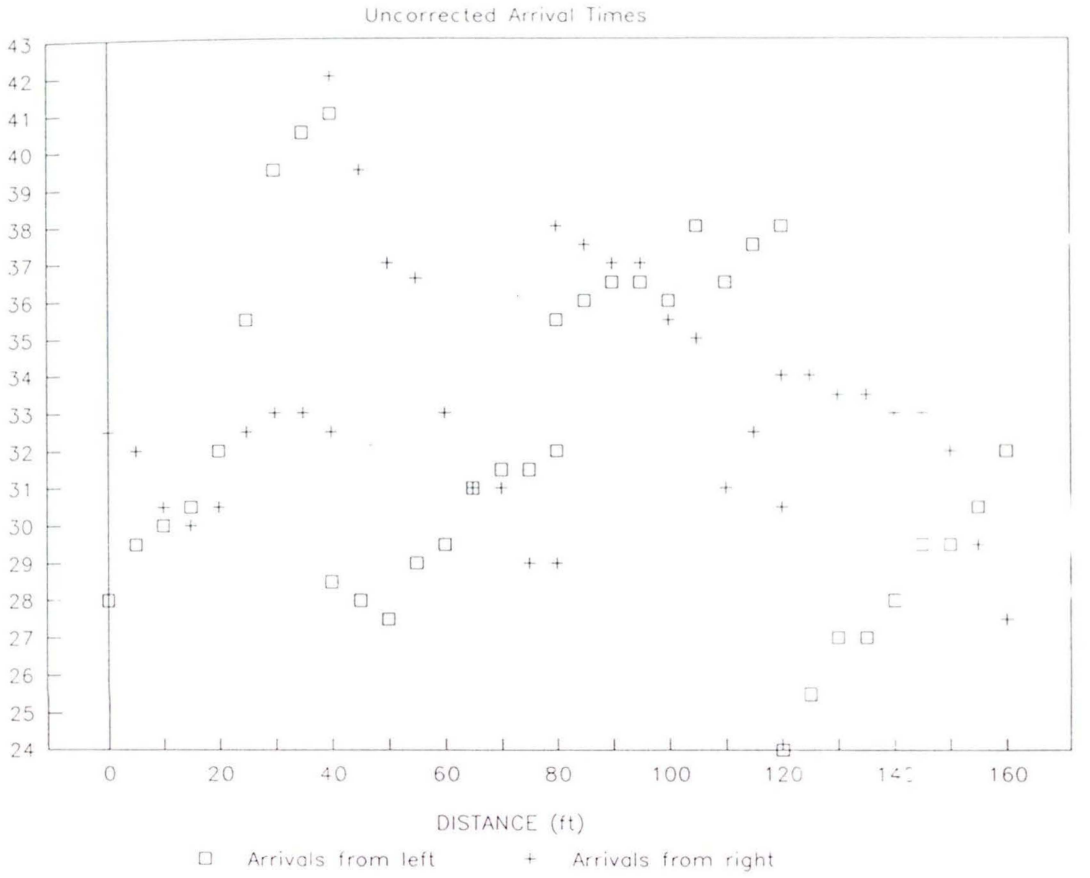


Figure 20. Uncorrected refraction times at Site 1.

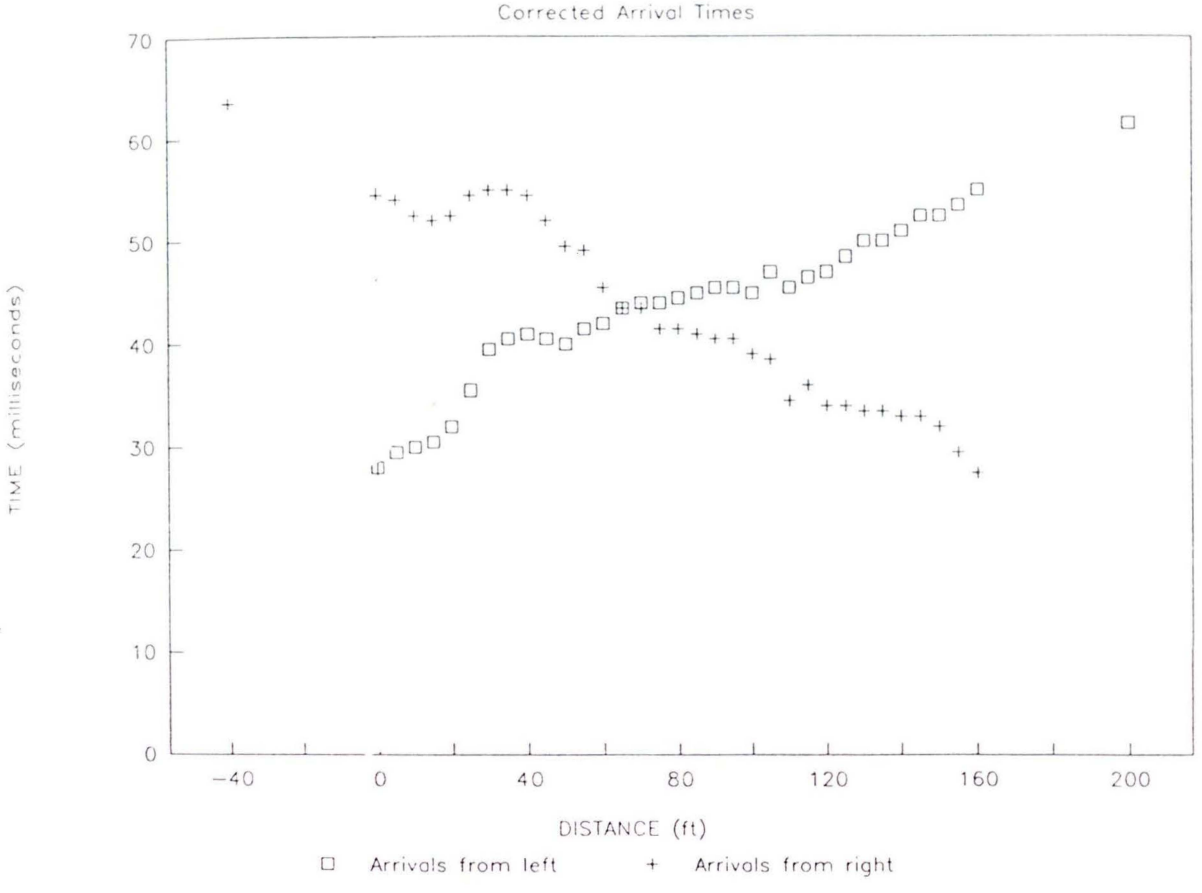
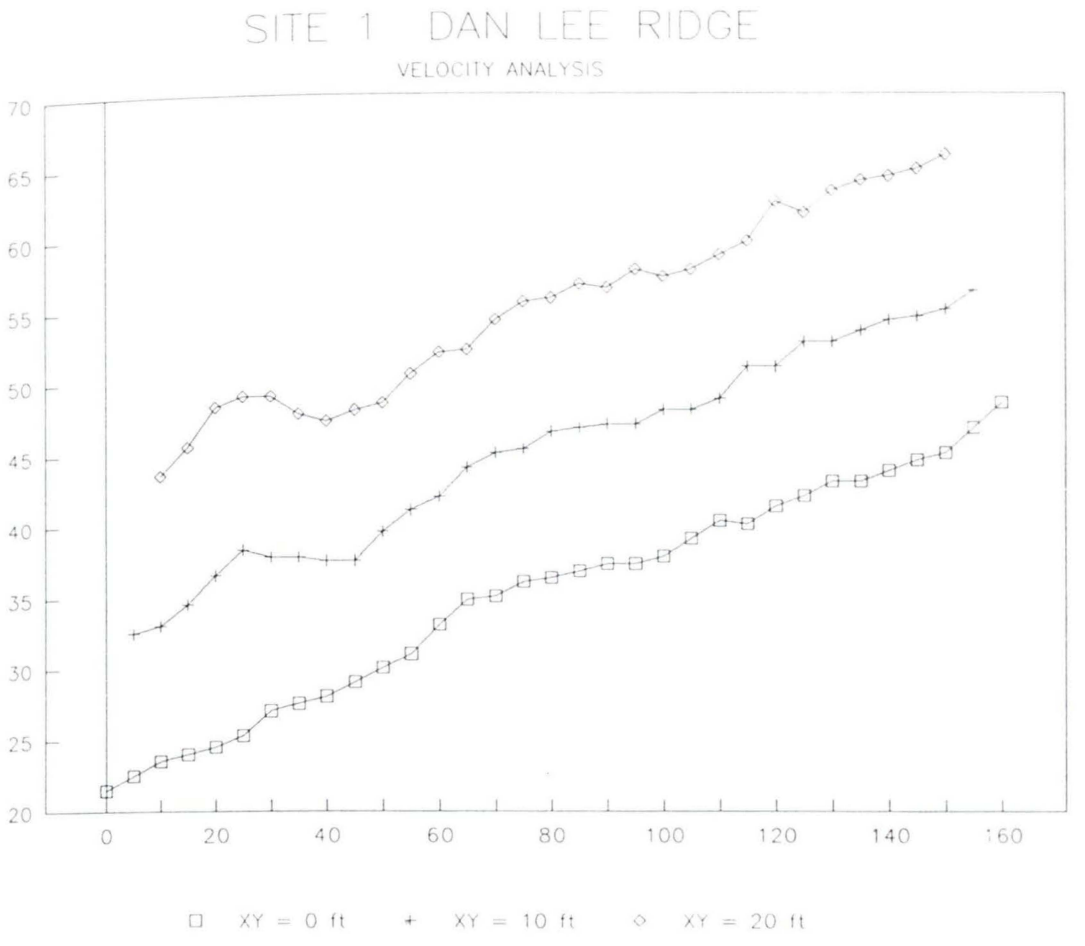


Figure 21. Corrected refraction times at Site 1.



XY SEP	V2 in ft/s	% ERROR	VARIANCE
0	6242.433	1.918085	.7062026
XY SEP	V2 in ft/s	% ERROR	VARIANCE
1	6358.678	2.067671	.7211304
XY SEP	V2 in ft/s	% ERROR	VARIANCE
2	6452.621	2.355504	.8262034
XY SEP	V2 in ft/s	% ERROR	VARIANCE
3	6527.548	2.815749	1.045508
XY SEP	V2 in ft/s	% ERROR	VARIANCE
4	6622.517	3.191875	1.178913

Figure 22. Velocity analysis at Site 1.

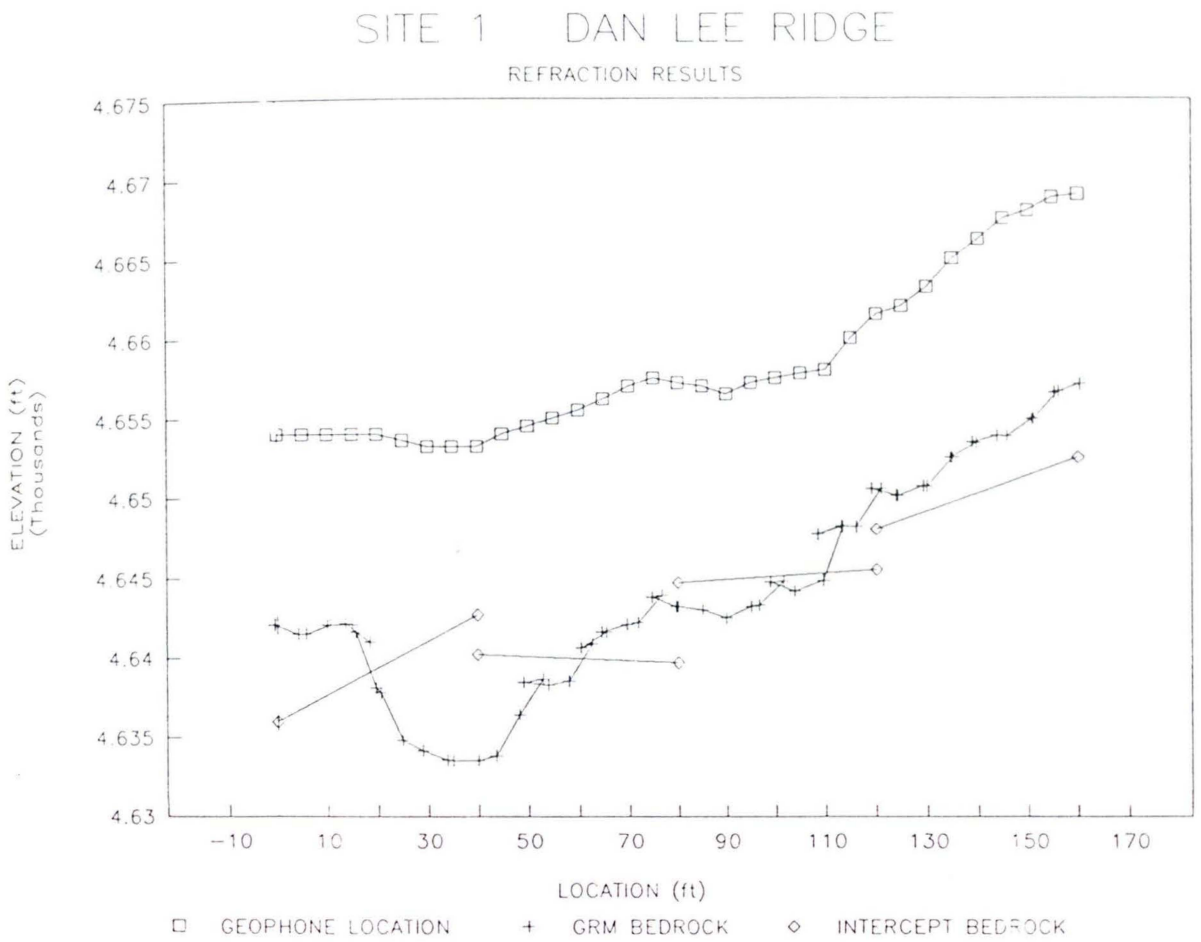


Figure 23. Comparison of GRM and intercept method results at Site 1.

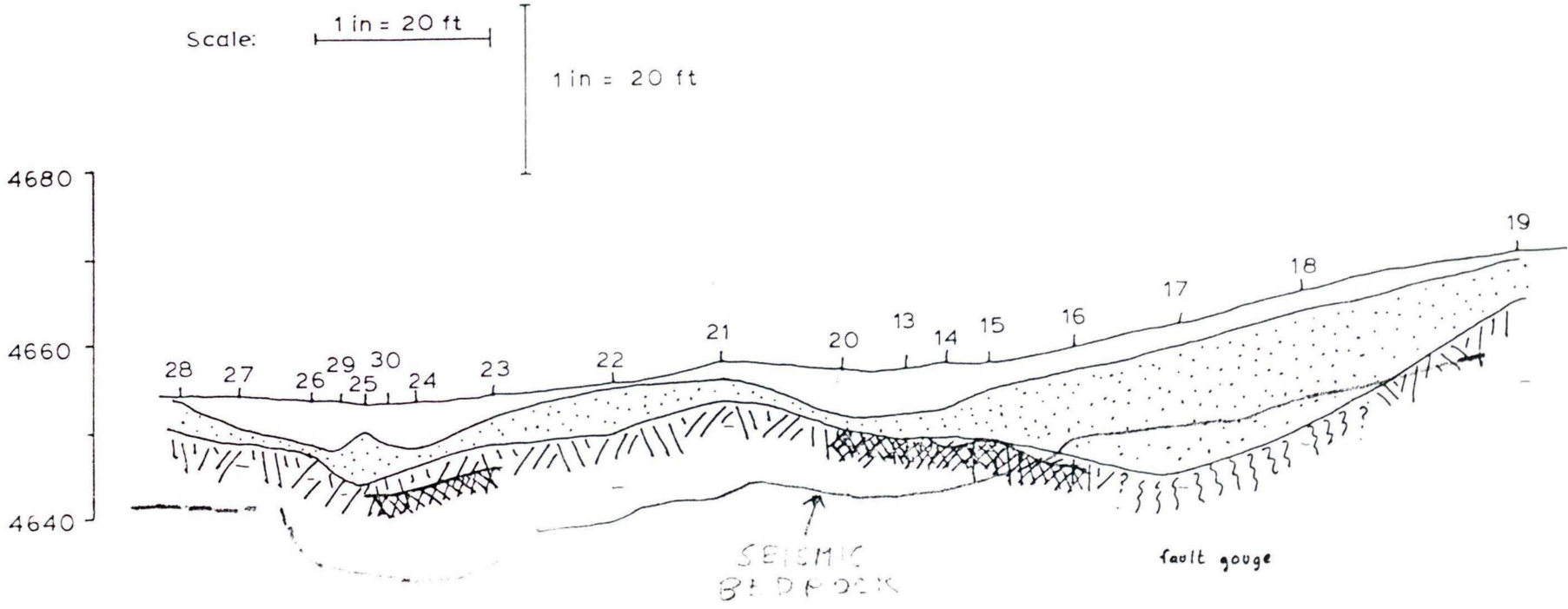


Figure 24. Comparison of GRM results with geology at Site 1.

Site 2

Refraction surveys were performed on Lines 1 and 5 at Site 2 (Figure 25). The head wave arrivals for each line are shown in Figure 26. The mean direct wave velocity (V1) was found to be 1130 ft/s.

Program SEIS13J was used to perform a velocity analysis of each line. The computer output (Figure 27) shows the optimum XY distance to be 0 ft. Line 1 produced an optimum V2 of 10100 ft/s and Line 2 showed a bedrock velocity of 11250 ft/s.

A comparison of the GRM bedrock surface and that obtained using the intercept method with shots at the end of the lines (Figure 28) shows much more detail on the bedrock surface using the GRM. The depths of the GRM and intercept method results generally agree on both lines.

The seismic bedrock surface and the geology from the drill holes for Line 1 (Figure 29) shows the seismic bedrock surface to be 7 to 10 feet deeper than the residual soil surface. The shape of the residual surface can be seen, however, in the seismic bedrock surface. Line 5 (Figure 30) shows the seismic bedrock 4 to 6 feet below the residual surface. However, the shape of the bedrock surface seems to bear no relation to the shape of the overlying residual soil surface.

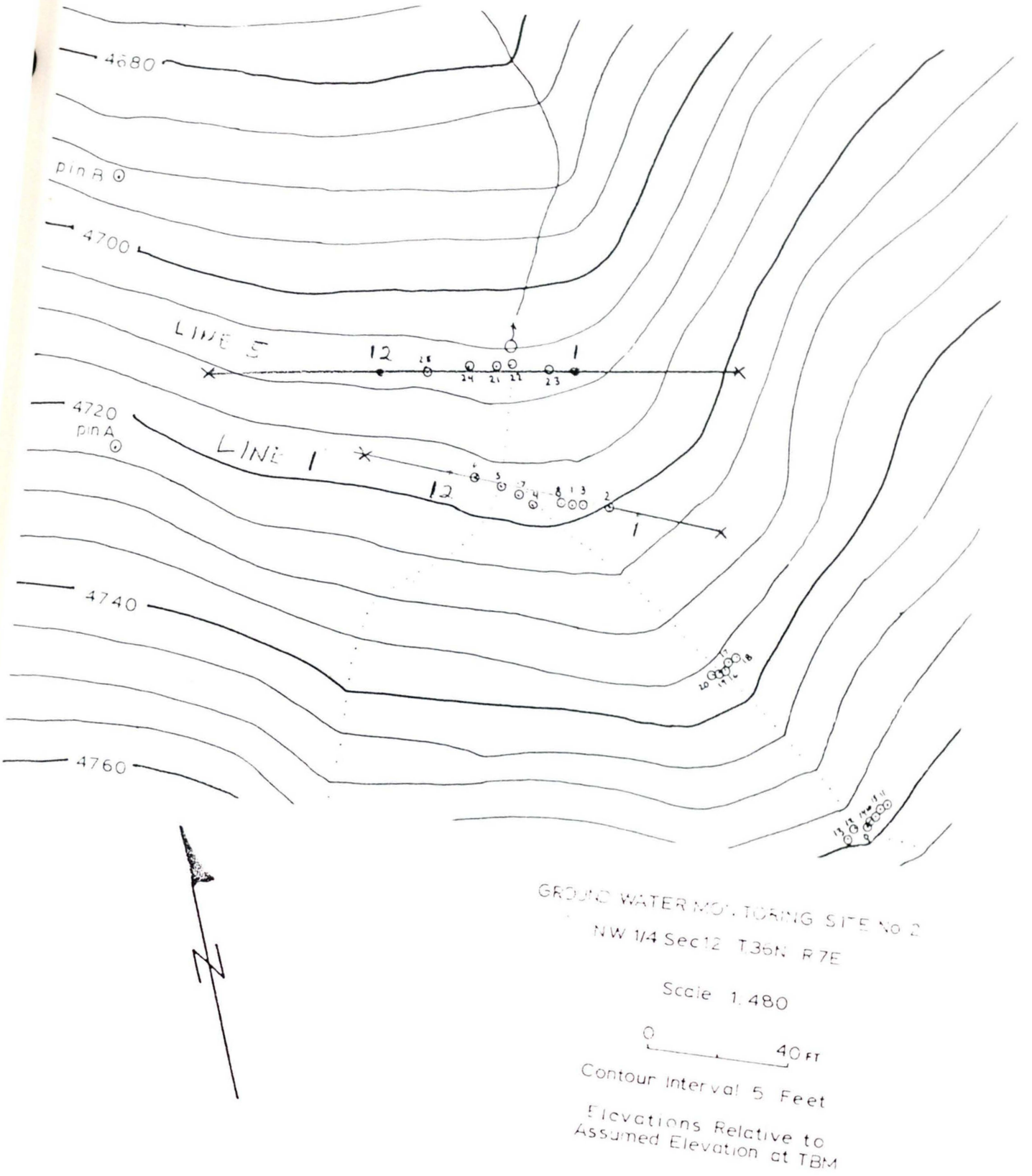


Figure 25. Location of seismic lines at Site 2.

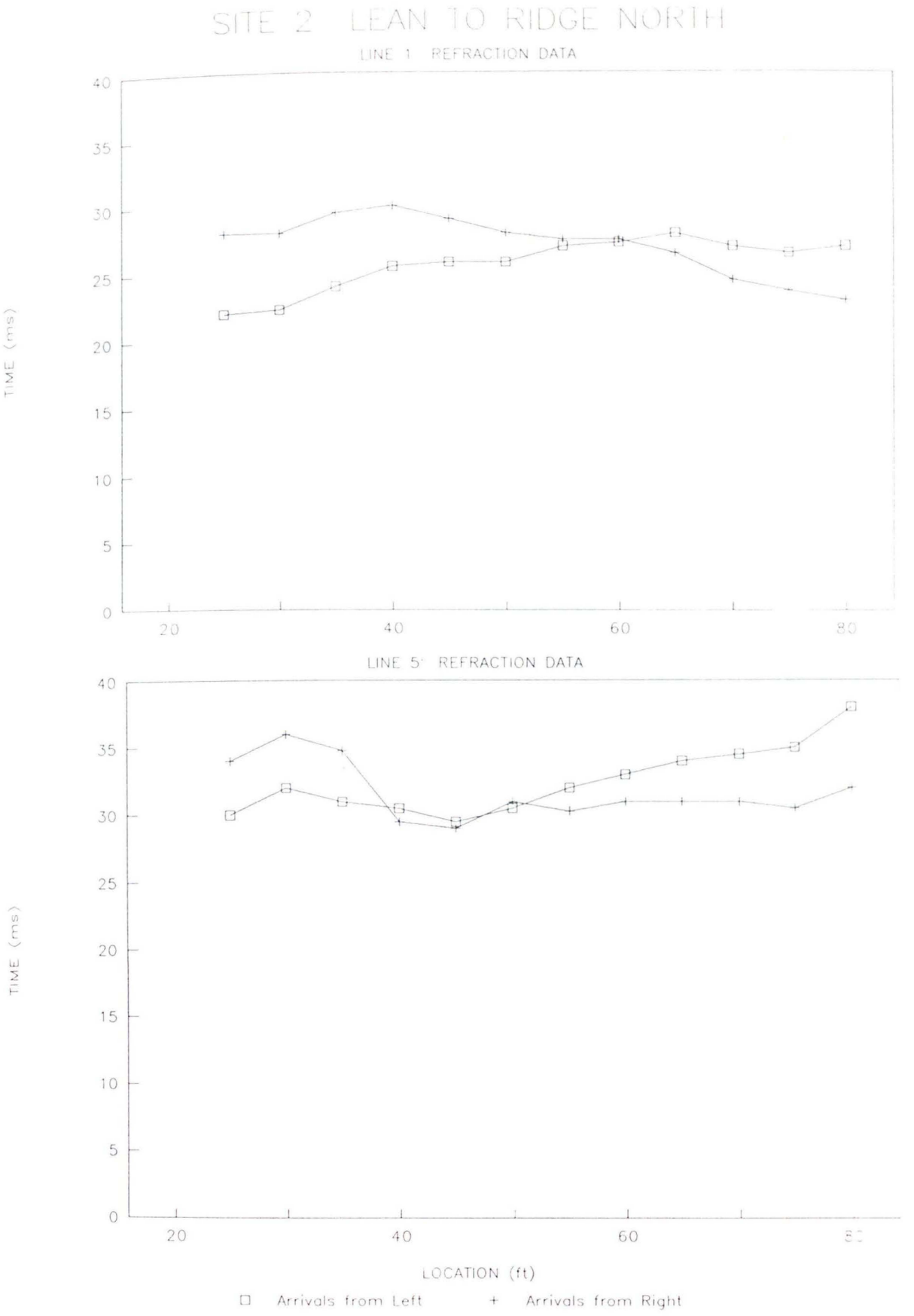


Figure 26. Refraction times at Site 2.

```
Reciprocal Time in msec.? 34.3
Geophone Separation in ft? 5
Number of geophone locations? 12
Data File Name? line1.prn
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 0               10098.85        3.779752        5.007935E-02
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 1               11591.15        6.371435        8.309105E-02
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 2               15363.04        15.65019        .214032
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 3               23999.67        24.58555        .1574131
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 4               34854.21        23.77141        4.884148E-02
Ok
```

```
Reciprocal Time in msec.? 45.5
Geophone Separation in ft? 5
Number of geophone locations? 12
Data File Name? line5.prn
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 0               11246.56        9.046921        .2313334
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 1               9640.666        12.48391        .4611262
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 2               7948.001        15.36936        .7712403
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 3               6593.432        17.22502        1.023736
XY SEP          V2 in ft/s      % ERROR         VARIANCE
 4               5529.983        15.60998        .8366547
Ok
```

Figure 27. Velocity analysis output for Site 2.

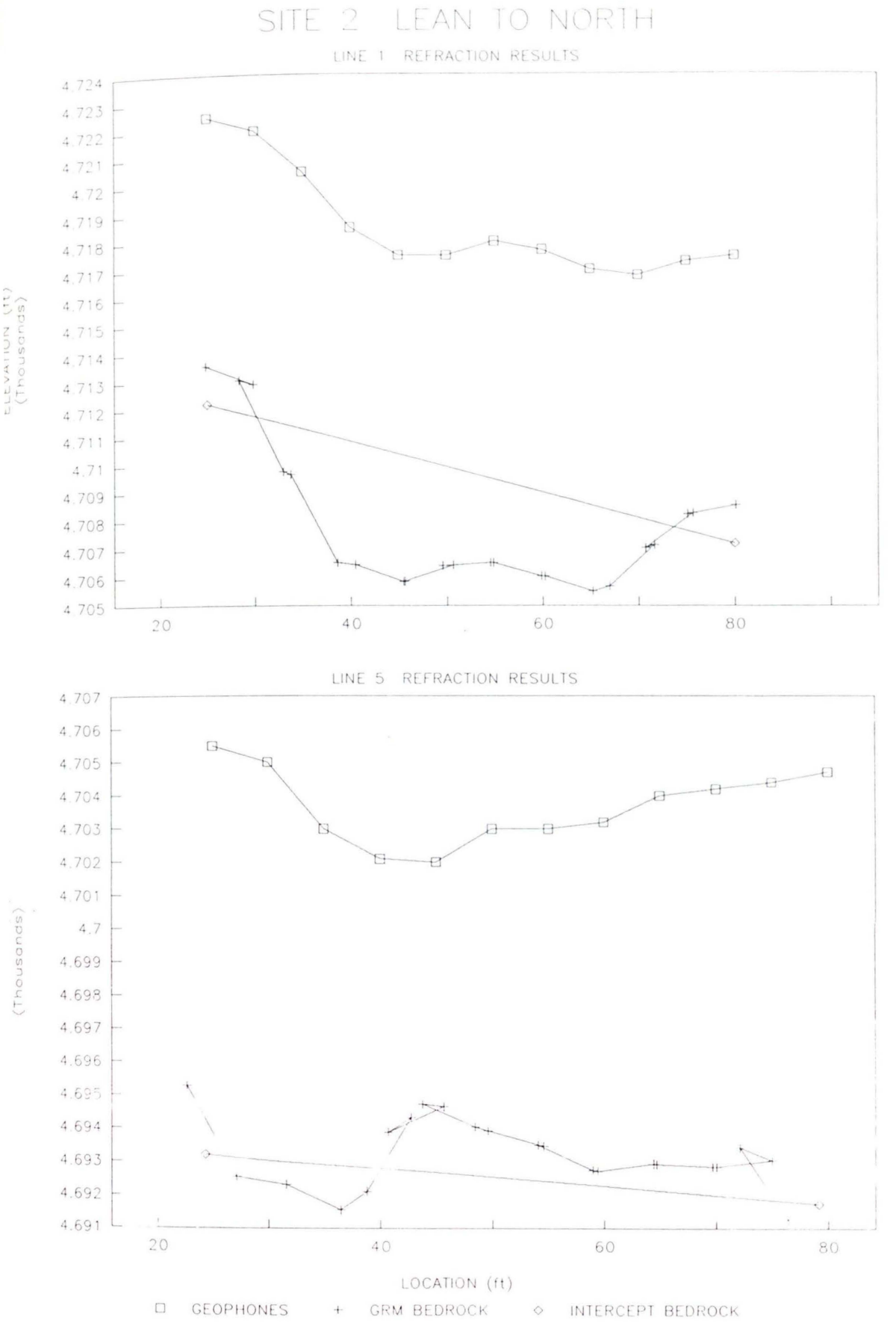


Figure 28. Comparison of GRM and intercept results at Site 2.

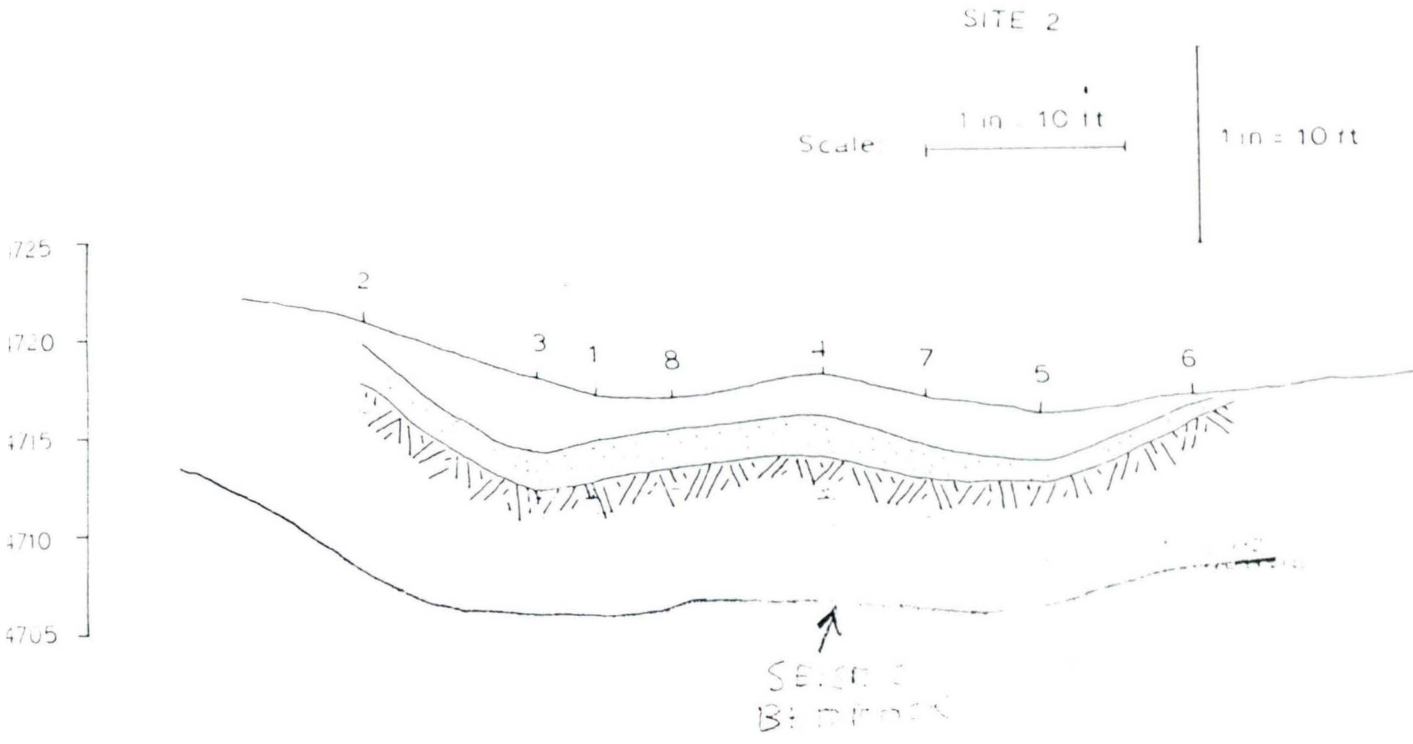


Figure 29. Comparison of GRM results with geology on Line 1.

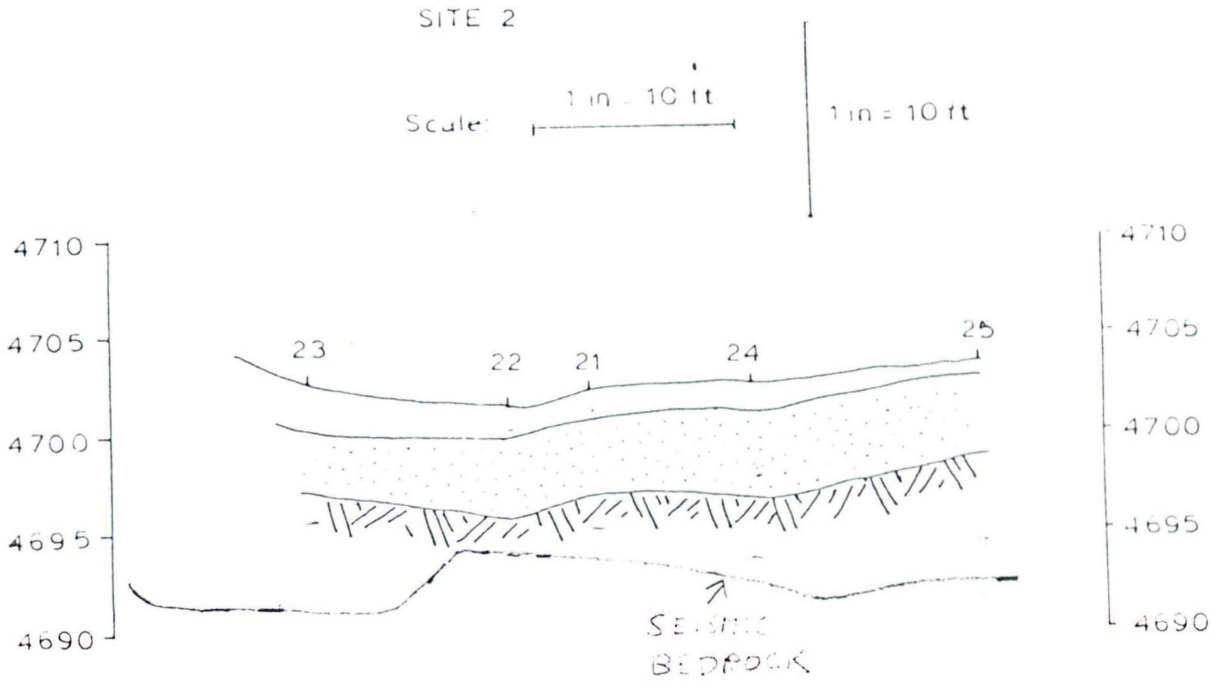


Figure 30. Comparison of GRM results with geology on Line 5.

Site 3

Seismic refraction data were collected along two intersecting lines at the site in 1983. A Geometrics ES-1210F 12 channel seismograph was used with a sledge hammer source. Figure 32 shows the seismic lines along with locations of shotpoints and receivers.

For each line, 12 geophones were planted 5 ft apart. Nine shots were taken at various locations relative to the receiver spread. The field records obtained were of high quality. Picks of first arrival times were easily made. Figure 18 shows a typical field record.

Figure 31 shows the time-distance curves for both lines. The locations of the shotpoints are apparent as are the arrival times at each geophone for each shot.

For landslide hazard evaluation, spatial variation (i.e. the mean and variance) of the soil thickness at the site are required. We used two different interpretational schemes to arrive at these values:

1. Each shot was treated independently and analyzed using the intercept method for a single layer over a half-space. This resulted in 18 estimates of soil thickness from which the mean and variance was directly calculated.

2) The generalized reciprocal method (GRM) was used to find the thickness at each geophone location. The mean and variance of the soil thickness was then calculated from these 24 values.

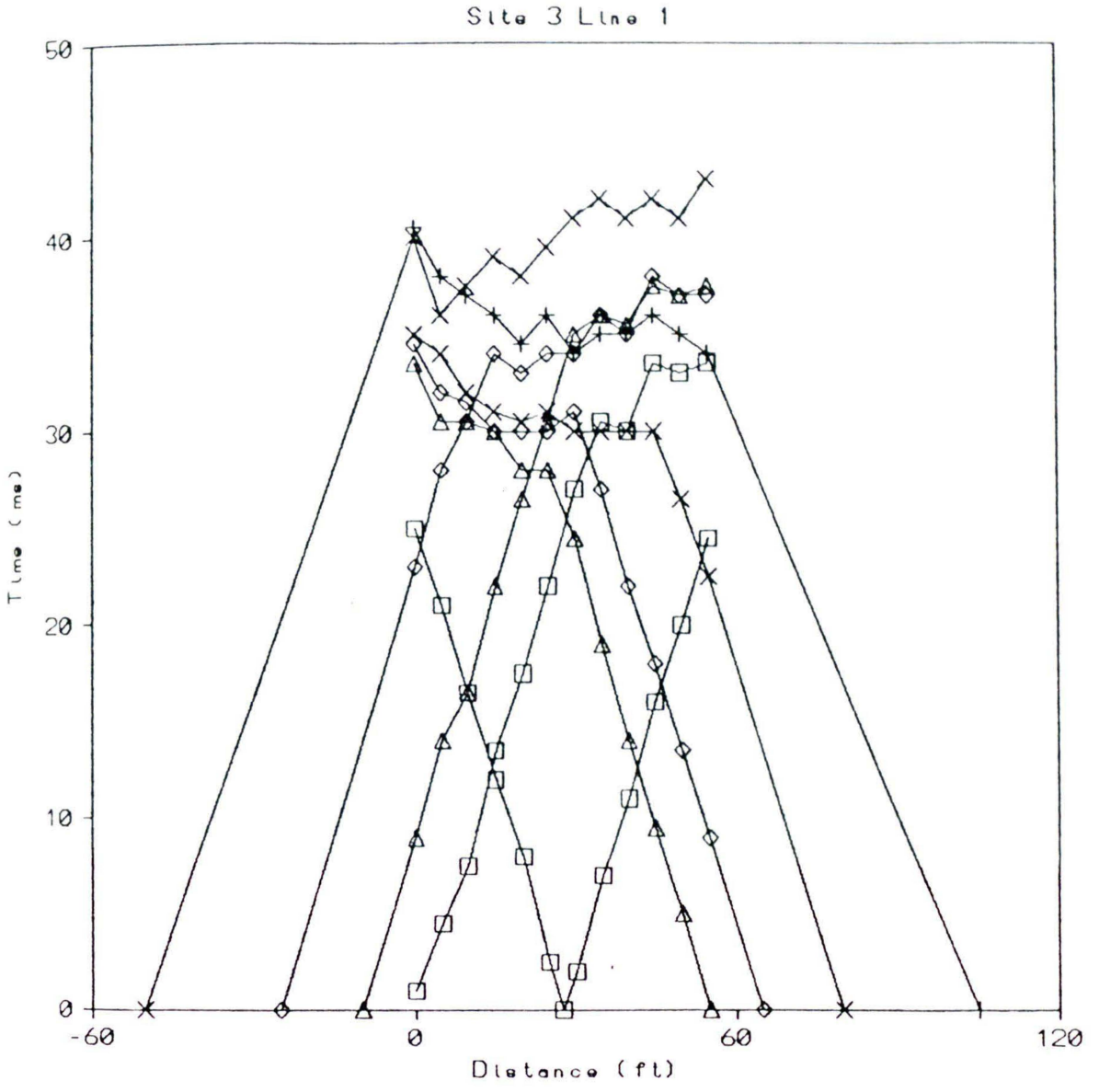


Figure 31. Time-distance curves obtained at the Lean-To site.

The first method combines the results from a relatively simple interpretational procedure; the second method combines the results of a sophisticated interpretational procedure.

Figure 33 shows all the direct-wave arrival times measured at the site irrespective of the shot location. A best-fit line through these data yielded a velocity of 1130 +/- 23 ft/s. The low variance of this result indicates that the top layer velocity is very consistent across the site. Hence a soil velocity of 1130 ft/s was used in all calculations.

Table 2 shows the results of analyzing each of the 18 shots individually using the simple single layer over a half-space formula. We applied this method because it is the most commonly used interpretational scheme for soil thickness used by forest engineers. For each shot, the head-wave velocity and intercept time were independently measured from the time-distance data (Figure 31) by fitting best-fit lines in a least-squares sense. For some shots, insufficient data was obtained for the final soil thickness computation. The mean and standard deviation of the soil thickness was found to be 15.3 +/- 2.3 ft.

To employ the GRM to the site, the travel-time data for each line was reduced to the case of a reversed refraction profile with shots offset from each end of the spreads far enough that each phone recorded a head-wave arrival from bedrock. The reciprocal time (Tab) between the two shots was also computed. The velocity of the surface soil layer was

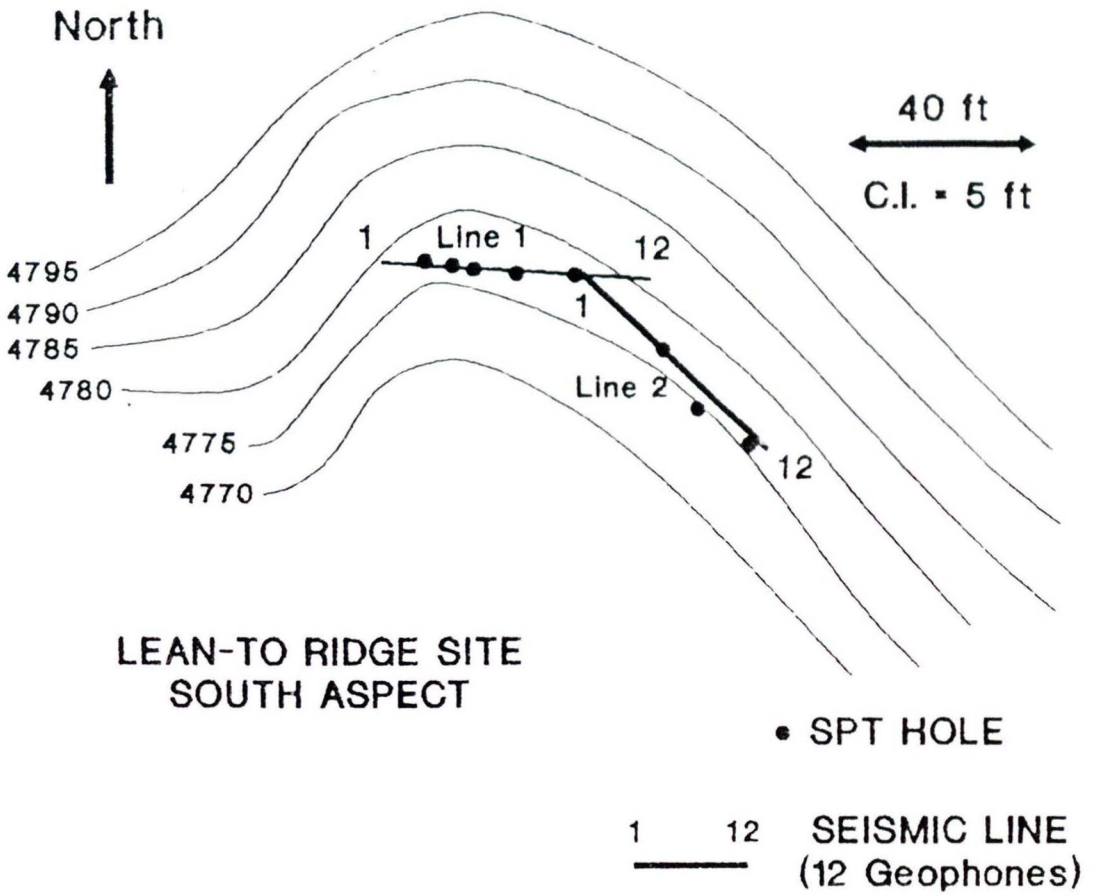


Figure 32. Seismic lines at the Lean-To Ridge study site.

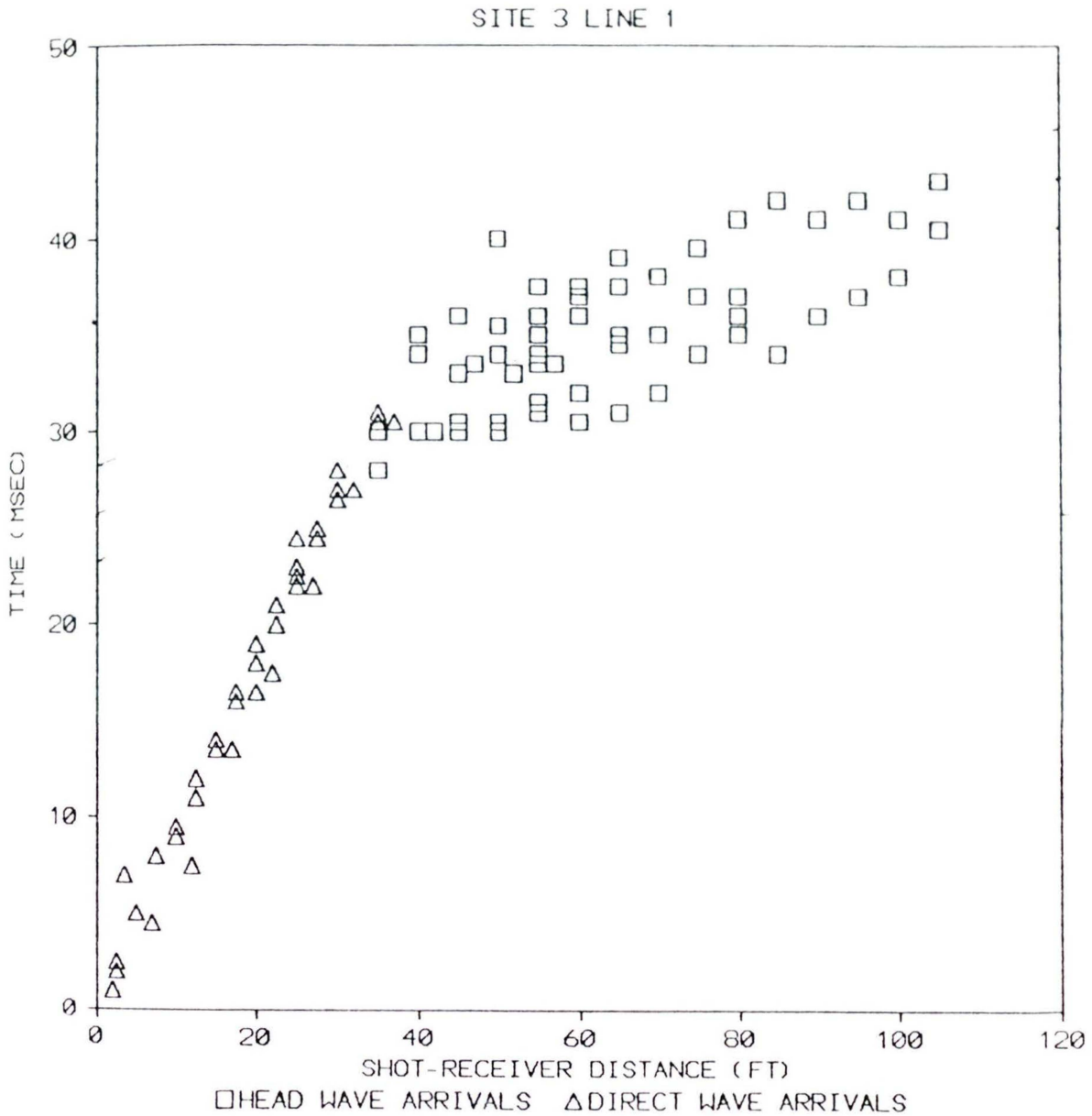


Figure 33. Direct wave arrival times measured at Site 3, Lean-To Ridge.

derived from the mean slope of the direct wave arrivals. The optimum XY value and the velocity of the bedrock were derived from a velocity analysis. Table 3 shows the results of the GRM at each geophone location on the two lines. The mean and standard deviation of the soil thickness was found to be 15.5 +/- 1.1 ft.

Both interpretational techniques provided consistent estimates of the mean and variance of the soil thickness at the site. Now, we compare these seismic results with drill hole data. Prior to the seismic refraction survey, eight holes drilled with a SPT split spoon sampler existed at the site. These eight holes are shown on a schematic cross-section (Figure 34). The depth to the residual soil surface in these wells was reported as 4 to 9 ft. The mean value found (5.5 ft) is only about one third of the seismic estimates of depth to bedrock.

Can the seismic results be incorrect? The seismic soil thicknesses depend primarily on intercept time and the velocity of the soil; the velocity of bedrock is of secondary importance. Intercept times depend on proper picking of first arrival times and on the calibration of the seismograph. However, the records obtained at the site (Figure 18) were of excellent quality and the instrument calibration for the seismograph used has been checked on numerous occasions. Hence, errors in timing cannot be the source of the errors.

The determination of top layer velocity depends on proper picking of the direct wave. The velocity of the direct wave, according to the least squares analysis, was 1130 ft/s +/- 2%. This is a highly precise result which happens to be the speed of sound in air. It is typical of

seismic waves to travel at the speed of sound in unsaturated soils. The complication here is that the "air" wave may have been picked as the first arrival--the true first arrivals from the soil layer being missed. However, re-examination of the field records shows absolutely no evidence on any record of a low amplitude first arrival before the air wave.

We later performed a down-hole seismic experiment on holes 9 and 10 which were drilled after the seismic refraction experiment. A geophone was lowered to the bottom of the holes and transmission time from surface to the hole bottom was determined. The mean velocity was found to be completely consistent with the surface seismic results.

Even if a faster top-layer velocity were used, the fit between the seismic soil thickness and the depth to refusal in wells 1 to 8 would not be improved. A higher top-layer velocity would result in even deeper estimates of depth to bedrock. Hence, the discrepancy between the borehole and seismic results is not due to the seismic procedure or the interpretation of the data.

The only reasonable explanation is that seismic refraction does not respond to the residual soil surface but rather to a more competent deeper bedrock contact. To check this hypothesis, we drilled two new SPT split spoon sample holes at the site. This time, we took great care to account for sloughing in the hole by cleaning the hole often. With much effort, we achieved depths of 12.9 ft and 15 ft before refusal. These depths were very consistent with the seismic results. As a final test, a core drilling rig was brought in with the purpose of sampling

bedrock. The net thickness of unconsolidated material was found to be 16.2 ft, a value in excellent agreement with the seismic results.

DISCUSSION

The seismic results at the three sites in granitic-metamorphic terrain generally showed seismic bedrock well below the residual soil surface. Below the eolian and colluvial soils, the residual soil was found to be residual tan colored granitic and gneissic unconsolidated rock material. The residual nature of this material was apparent due to preserved metamorphic structures as well as cross-cutting weathered quartz veins.

The effect of microfractures in the residual soil will strongly affect seismic velocities and thus the interpretation of seismic refraction and reflection results. Theoretically, the velocity of seismic waves in rock depends exclusively on elastic properties and density. However, in practice, a network of fissures in a rock superimposes an overriding effect (Fourmaintraux, 1976).

If Vm is the velocity of bedrock in the absence of pores or fissures, and if Va is the actual seismic velocity, then a rock quality index Q can be defined as

$$Q = Vm/Va$$

Experiments by Fourmaintraux established that the relationship between Q and porosity in non-fissured rock is as follows

$$Q = 1 - 1.6\ n.$$

However, if fissures exist, the above relationship does not hold. Seismic velocities can be seen to be extremely sensitive to fissuring. In the gruss-covered terrain of central Idaho, the decrease in the amount of weathering, fissuring, and porosity with depth will produce a corresponding increase in seismic velocity.

Seismic refraction is ideal for finding the net thickness of weathered material in the gruss-covered environment. The subtle change from unweathered bedrock to weathered gruss apparently produces a large change in elastic properties that is readily detected seismically. On the other hand, seismic refraction can fail to detect the boundary between residual gruss and the overlying colluvial soil. This boundary represents a potential slip surface because of a large change in hydraulic conductivity. Perched water and high pore pressures may occur immediately above it. At our study site, the refraction method responded neither to the perched water nor to the change in soil texture. We recommend that seismic refraction methods be used as a primary tool for finding net overburden thickness in gruss-covered terrain. However, other methods must be used to delineate the more subtle boundary between residual gruss and colluvial soils.

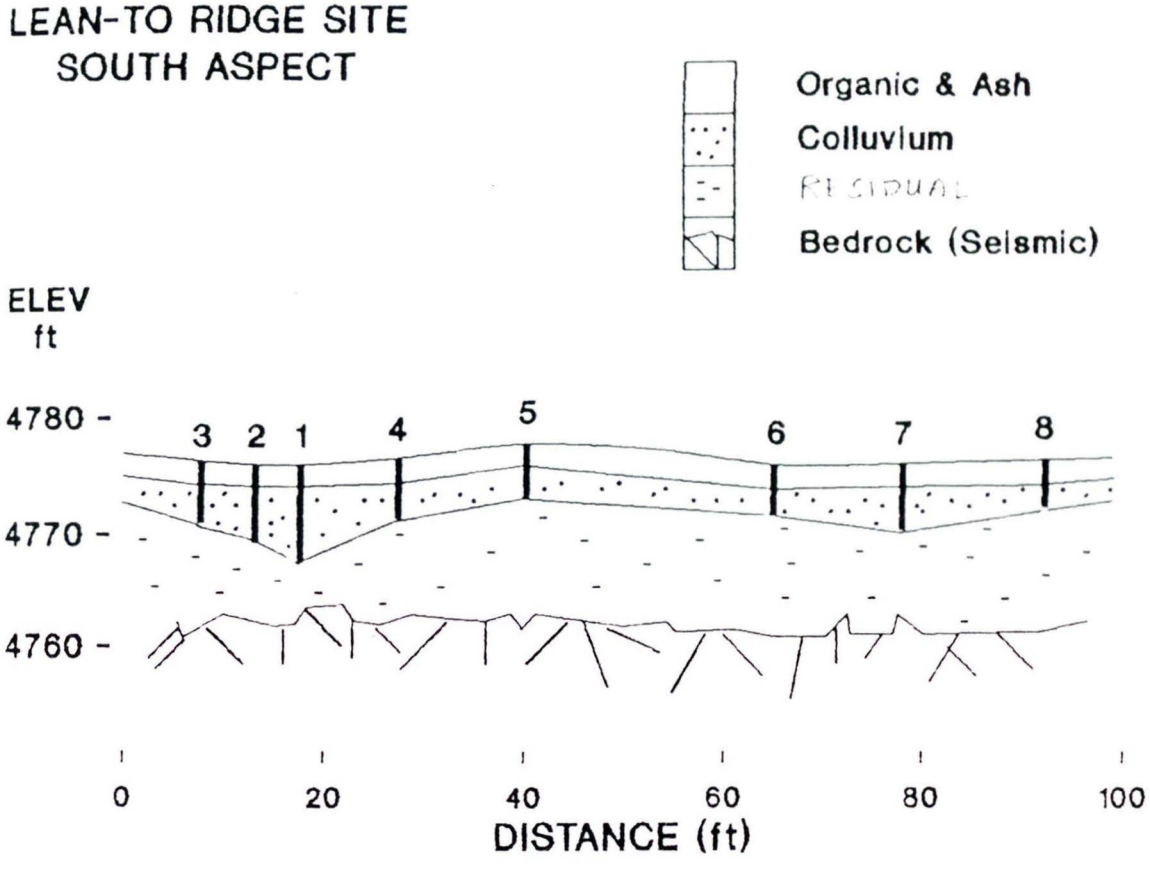


Figure 34. Comparison of GRM bedrock and geology from drill holes at Site 3.

LINE	SHOT	V1	V2	Xcr	Ti	Z	PE
1	1	1130	5560	34.0	0.024	13.8	10%
1	2	1130	9890	39.7	0.031	17.7	4%
1	3	1130	9090	37.0	0.029	16.4	4%
1	4	1130	11100	41.6	0.033	18.8	4%
1	6	1130	4347	30.8	0.020	11.8	9%
1	7	1130	5833	31.3	0.022	12.9	8%
1	8	1130	8330	31.8	0.024	13.9	5%
1	9	1130	12900	37.0	0.030	17.0	5%
2	1	1130	10000	31.8	0.032	14.2	5%
2	2	1130	15900	32.9	0.027	15.3	1%
2	3	1130	15800	33.7	0.028	15.7	2%
2	4	1130	23100	40.0	0.034	19.0	3%
2	6	1130	5560	30.8	0.022	12.6	16%
2	7	1130	5490	29.7	0.021	12.6	9%
2	8	1130	4690	36.8	0.025	14.4	7%
2	9	1130	9140	42.8	0.033	18.9	3%
			-----			----	
Mean and SD			9790	+/- 4940		15.3	+/- 2.3

Table 2. Spreadsheet for calculating soil thickness using the intercept method, a simple interpretational procedure.

	LINE 1 (Tab=50)			LINE 2 (Tab=51.5)		
Phone	Ta	Tb	Z	Ta	Tb	Z
1	40	40.5	17.3	34.7	44	15.4
2	36.3	38.3	13.9	38	46	18.4
3	37.5	37	13.9	36	43.5	15.9
4	39	36	14.2	36.7	43	16.0
5	38	34.5	12.8	36.5	42	15.3
6	39.5	36	14.5	36.3	42.5	15.5
7	41	34	14.2	37	41.3	15.2
8	42	35	15.3	36	39	13.3
9	41	35	14.8	38	40.5	15.3
10	42	36	15.9	38.5	40	15.3
11	41	35	14.8	38.5	40	15.3
12	43	34	15.3	38	39	14.5
			-----			-----
Mean and SD			14.7 +/- 1.1			15.5 +/- 1.1

Overall Mean and SD 15.1 +/- 1.1 ft

Velocity of Top Layer = 1130 ft/s
Velocity of Bottom Layer = 13,300 +/- 930 ft/s
XY=0

Table 3. Spreadsheet for finding soil thickness using the GRM, a sophisticated interpretational technique.

SHALLOW SEISMIC REFLECTION METHOD

BASIC PRINCIPLES

The oil industry has made great advances in deep seismic reflection work, but little research has been done with shallow seismic reflection for engineering purposes. The seismic reflection method has not been used extensively because of the difficulty of identifying reflections from shallow depths. Amplitudes of reflected waves, when present, are smaller than the amplitude of unwanted waves, particularly ground roll consisting of Rayleigh waves and Love waves.

Energy sources that have been tried with shallow reflection surveys include the sledge hammer (Meidav, 1969), weight drop, and small explosive charges (Pakiser and Warrick, 1956). These sources produce seismic waves with a dominant frequency below 100 Hz. In order to provide better precision, accuracy, and resolution for shallow reflection surveys, higher frequency sources are necessary, as well as higher frequency detectors. In seismic reflection, the resolution of thin beds is limited to about 1/8th of the wavelength of the seismic energy (Widess, 1973). Hence, by increasing the frequency of seismic reflection surveys, the resolution can be increased.

The conventional shallow reflection technique requires the use of a multi-channel seismograph in that reflections might be distinguished from other seismic events such as surface waves and multiple refractions. The high resolution required for shallow reflection work requires the use of high frequency sources and receivers. Very few

studies in the past have dealt with the problem of shallow reflection seismology. Allen and others (1952) observed reflections from bedrock at depths of 100-150 m. Further developmental work in the 1950's featured fast-acting analog circuits involving automatic gain control, direct wave suppression, frequency filters, fast paper speed, and even piezo-electric sources (Olson, 1955; Pakiser and others, 1954; Pakiser and Warrick, 1956; Zietz and Pakiser, 1957). Cook (1965) used the reflection method for cavity detection. Meidav (1969) reported shallow reflections using a hammer source. Costain and Robinson (1972) measured many reflectors in the depth range of 40 to 300 m on the east coast. Mosman and others (1973) used a vibrator source for shallow reflection work. Hunter and others (1982) designed an optimum field technique for bedrock reflection mapping with a multichannel engineering seismograph. Steeples and Knapp (1982) found that a 22-caliber rifle fired from a Betsy Seisgun was a practical source for seismic reflections. In the best conventional shallow reflection results reported in the literature, Steeples and Knapp (1982), using digital low-cut filters and a 22-caliber source, were able to see reflections as shallow as 25 ft.

BASIC Program SEIS12 in the appendix computes the reflection time T at shot-receiver distance X for a given set of layer parameters. The user enters the velocity and thickness of each layer above a halfspace, the number of wave traverses in each layer, and the shot-receiver distance. The program uses an iterative procedure in conjunction with Snell's law to find the correct ray path. The net travel time is then calculated. This program can be used in a trial and error procedure to match theoretical and observed travel times, including multiply reflected waves.

Within the forest service, Cornell (1984) has had some success with a simplified seismic reflection technique using a single channel seismograph by placing a phone within a few feet of the source, thus avoiding surface waves and refracted noise. He found, for reflecting horizons greater than 3 ft thick, the reflected wave could be distinguished from the direct wave. A summary of his ideas and results are given below. Then we show the results of our experiments using his method at two northern Idaho test sites.

After several years of work on Forest Service projects where drilling and seismic refraction testing provided subsurface data, Cornell (1981) suggested a method to obtain reflection times with instruments designed for refraction testing. He called the method "Simplified Seismic Reflection" (SSR), because it uses only one receiver and a simplified method of calculation. Cornell's initial results appeared to have the same margin of error as refraction testing and he found the method to be very rapid. He further suggested that the depth to several interfaces could be calculated without significantly increasing the difficulty of operation or calculation.

The simplified formula used by Cornell is shown along with a schematic diagram of the reflection process in Figure 35. The derivation is based on the assumption that the surface wave will not interfere with the reflected waves at very short shot-receiver distances. To use the method, near surface seismic velocities must be known from separate refraction testing. The general procedure is to put the hammer plate and geophone very close together (Cornell used 6 inches) and to use very low gain on the seismograph unit.

Figure 36 illustrates one of Cornell's wave traces showing what he interprets as two major reflections. The reflection times were measured at the peaks. Cornell found that the depths calculated from such reflection peaks approximated the depths obtained by refraction results. The first wave on Figure 36 is thought to be the direct wave arrival which may interfere with reflectors from very shallow layers. However, Cornell claimed that valid reflections occur from depths as shallow as three feet.

Figure 37 shows data derived by Cornell from Forest Service projects on the Siskiyou National Forest. Cornell noted that some of these data were taken early in his study before the methodology was established, and that few attempts were made at the time to reconcile conflicting data because the method was experimental.

Critique of the SSR method.

A complicating factor, not explicitly treated by Cornell (1981), causes doubt about the SSR method. This factor relates to the seismic source. Although a hammer blow or an explosive shot may conceptually be considered as occurring in an instant of time, in practice, all seismic source signals have finite duration. If the seismic source were indeed a spike (Figure 38), then the SSR method could very possibly be practical. The reflections, even after some filtering by the earth, would also be impulsive (Figure 39).

Actual seismic sources produce waveforms that are extended over tens of milliseconds (Figure 39) and are composed or a series of crests and troughs. The sledge hammer impulse shown in Figure 39 is composed six identifiable crests. How would these peaks be distinguished from reflectors? To further confuse the problem, the reflectors must also be composed of a similar series of waves. For shallow reflectors, the latter peaks in the source wave will overlap with the multiple peaks in the reflected waveform. This would make it extremely difficult to identify true reflections.

FIELD TEST RESULTS

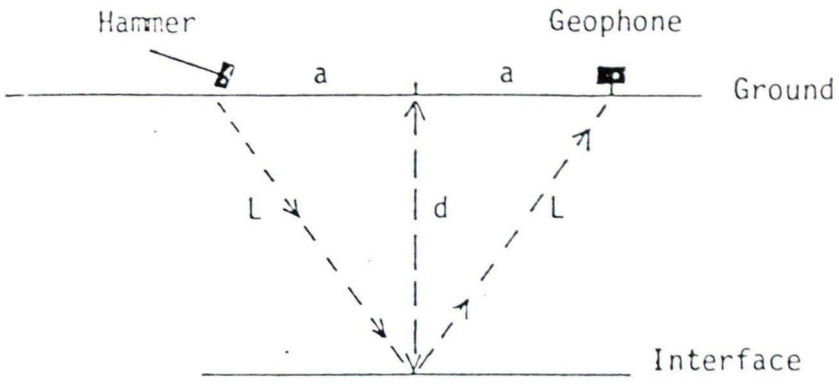
To evaluate the SSR technique, we tried it at Site 1 and Site 3. We used a Geometrics ES1210F seismograph with a low-cut filter set at 80 Hz, high frequency (100 Hz) geophones (conventional engineering seismograph geophones are about 8 Hz), and a 22-caliber source. The effectiveness of the 22 caliber source compared with a hammer source can be seen in the two records shown in Figure 42. The 22 caliber source definitely produced crisper seismic events on the records which were shot under identical conditions.

We placed the shots as close as possible to the phones without clipping the signal (about 2.5 ft). The results at Site 1 are shown in Figures 40 and 41. The response of the phones to the shots does show a definite variation with geology along the line. However, we generally found it difficult to decide which event to pick to represent the

subsurface geology. The same held true for the SSR results at Site 3 (Figures 43 and 44).

DISCUSSION

There is no question that the SSR method responds to site geology but, at present levels of understanding, the results are not easily interpretable. It is impossible to separate possible reflectors from other events (refractions, reflected refractions, surface waves, ringing of the source, ringing of the geophone). Although shallow reflection surveys from 25 feet or less may be possible with sophisticated equipment, engineering seismographs do not seem capable of this feat.



Derivation of formula for depth to first interface

V = Seismic velocity in feet per millisecond
T = Time measured by instrument in milliseconds
d = Layer thickness in feet
D = Total depth in feet of layers d_1, d_2, etc.

Given: 1) Velocity = $\frac{\text{Distance}}{\text{Time}}$ (by definition)

2) $L = \sqrt{a^2 + d^2}$ (by Pythagorean Theorem)

Then: $V = \frac{2L}{T}$

$$V = \frac{2\sqrt{a^2 + d^2}}{T}$$

When a = 0 or is negligible, the formula may be simplified to

$$d_1 = \sqrt{\frac{V^2T^2}{4}}$$

$$d_1 = \frac{VT}{2}$$

Therefore : $D_1 = d_1 = \frac{V_1T_1}{2}$

$$D_2 = d_1 + d_2 = \frac{V_1T_1}{2} + \frac{V_2(T_2 - T_1)}{2}$$

$$D_3 = d_1 + d_2 + d_3 = \frac{V_1T_1}{2} + \frac{V_2(T_2 - T_1)}{2} + \frac{V_3(T_3 - T_2)}{2}$$

Figure 35. Schematic diagram of the SSR method. After Cornell, 1984.

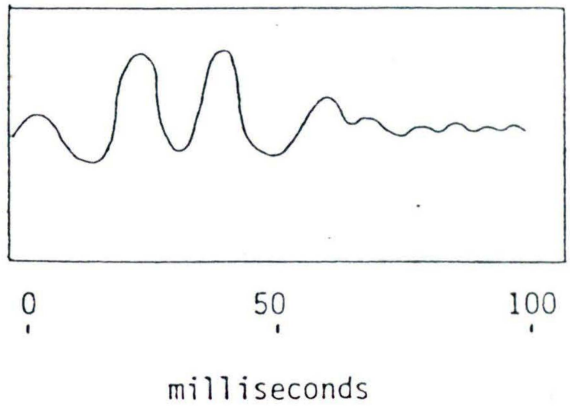


Figure 36. A typical wave trace showing two possible reflections. After Cornell, 1981.

Project	Layer	Depths (Feet) Drilling	Seismic Refraction	Simplified Reflection	Remarks
Tigertown Slump	D_1	19	20	20	Bedrock
Burned Timber Bridge	D_1	7	7	7	Bedrock
Bolan Creek Bridge	D_1	5	-	6	Water Level
	D_2	12	12	12	Bedrock
	D_1	5	-	4	Water Level
	D_2	7	7	6	Bedrock
Sucker Crk. Slump	D_1	-	4	9	Bedrock
	D_2	35	34	38	Saturated Silt
	D_1	42	43	45	Saturated Silt
	D_1	None	10	11	Bedrock
	D_2	None	31	33	Saturated Silt
Sucker Crk. Bridge	D_1	None	3	3	Gravel
	D_2	None	15	15	Bedrock
	D_1	None	6	5	Gravel
	D_2	None	17	25	Bedrock

Figure 37. Data derived by Cornell (1984) on various projects on the Siskiyou National Forest.

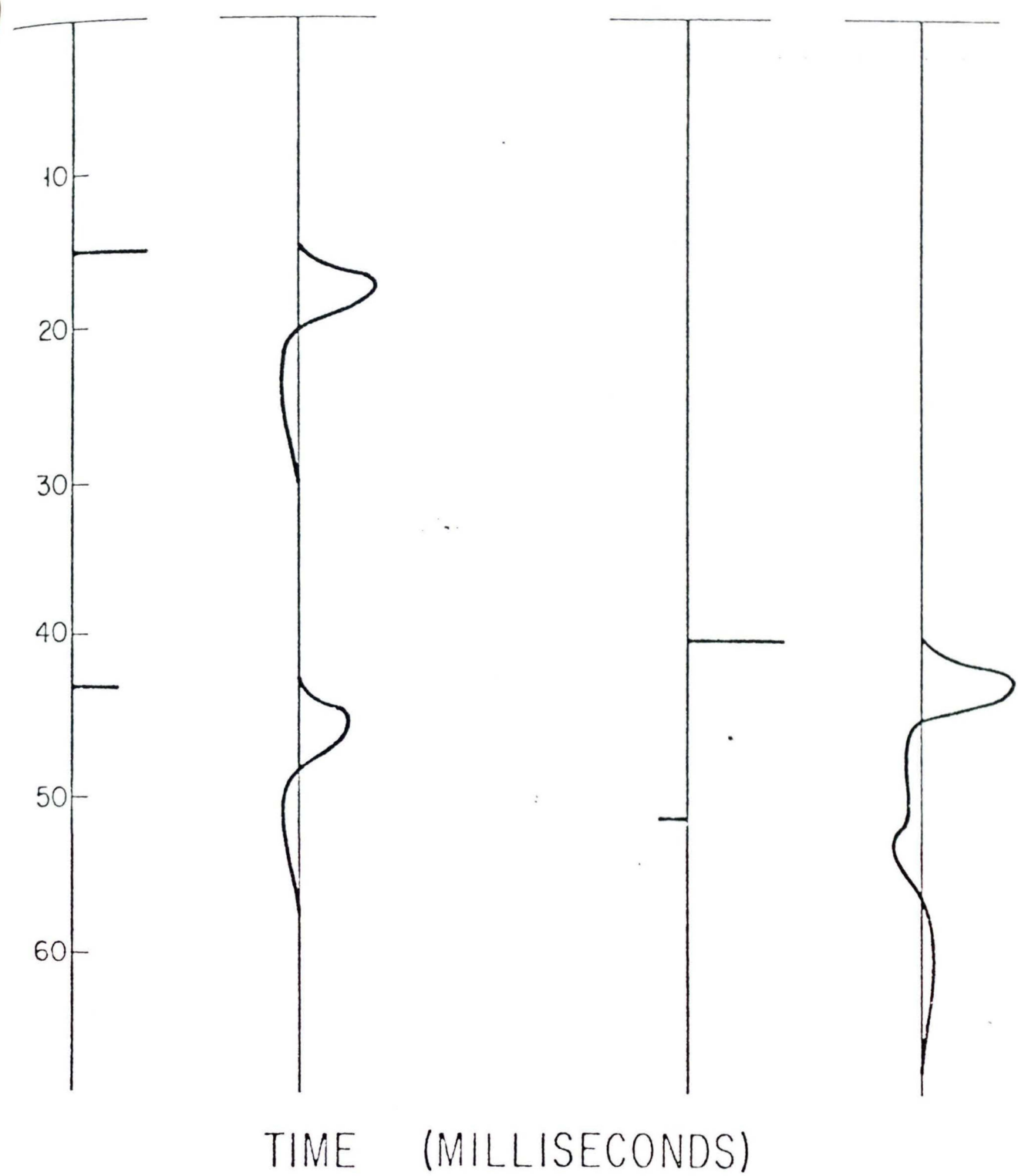


Figure 38. The spike-like nature of an ideal seismic source and reflection.

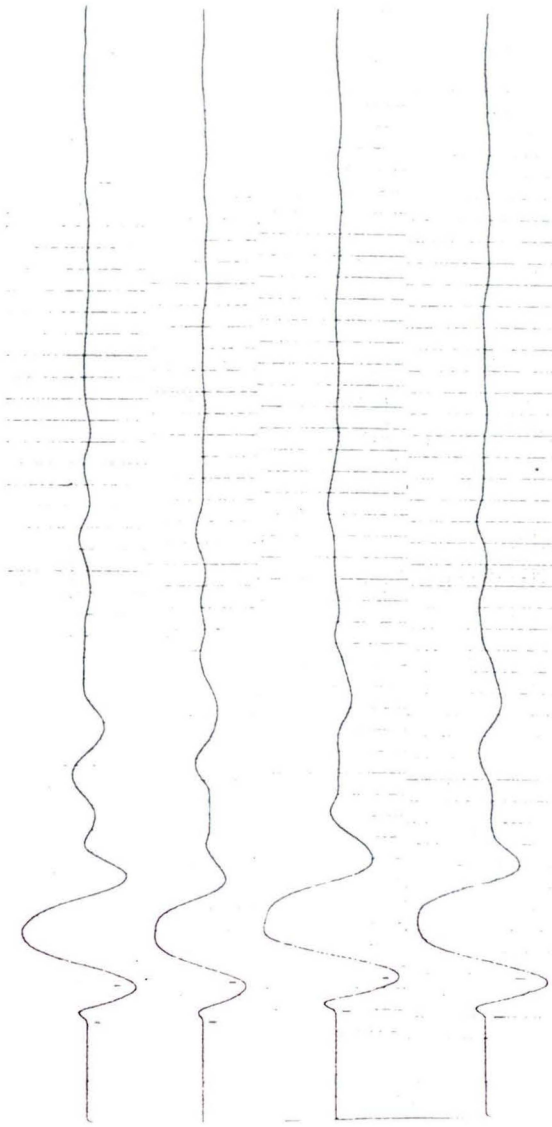


Figure 39. Waveforms produced by actual seismic sources.

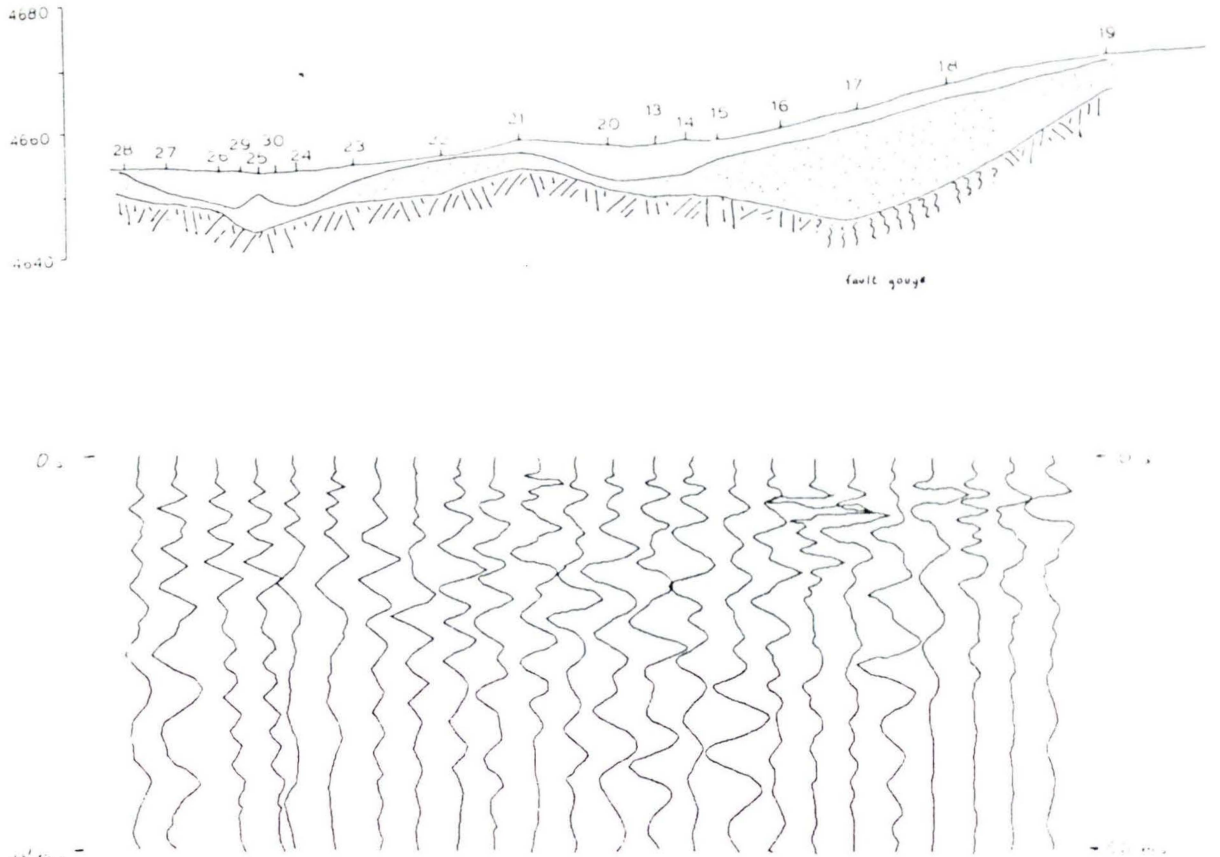


Figure 40. SSR data collected at the Dan Lee site, Line 1.

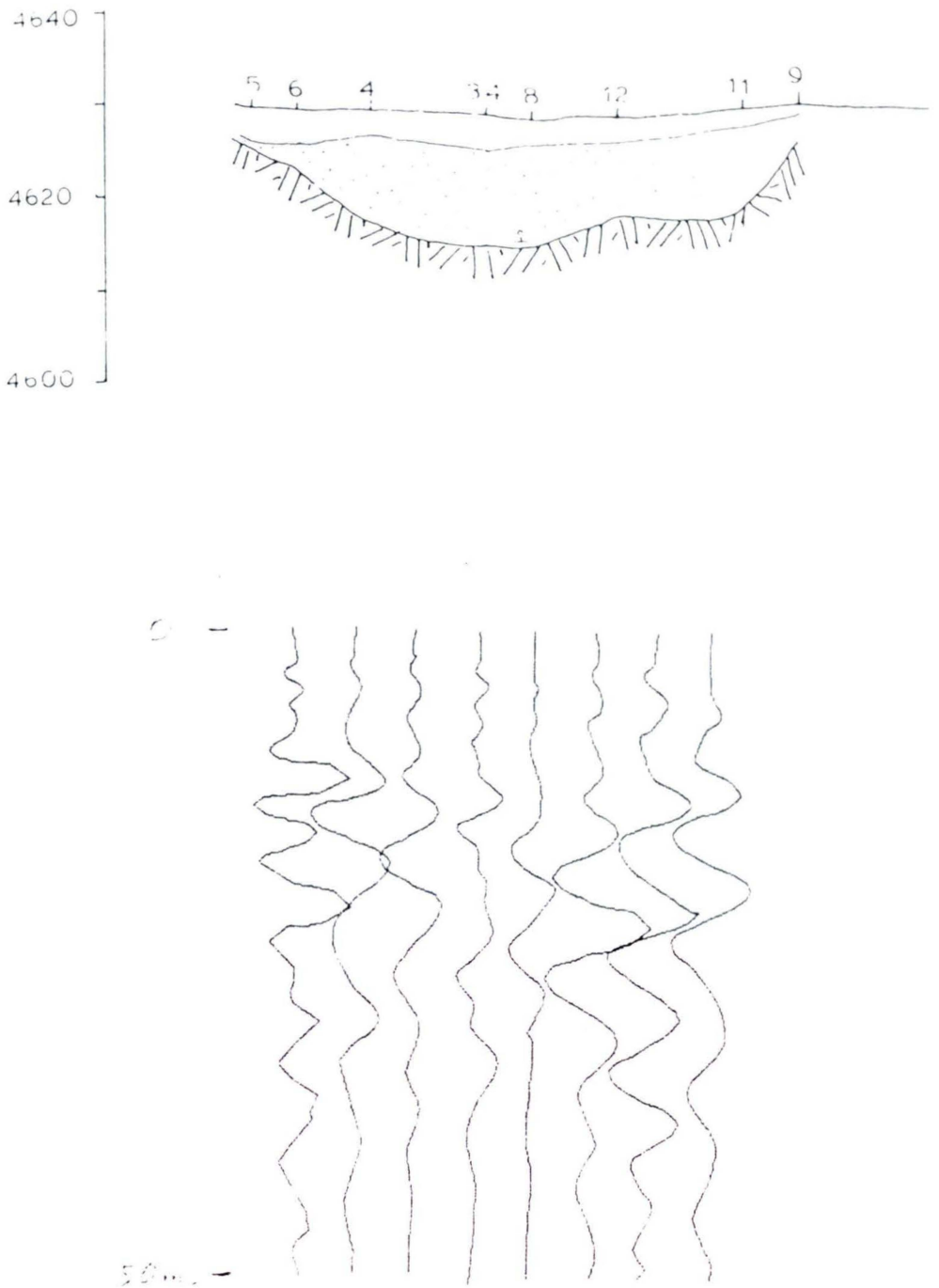


Figure 41. SSR data collected at the Dan Lee site, Line 2.

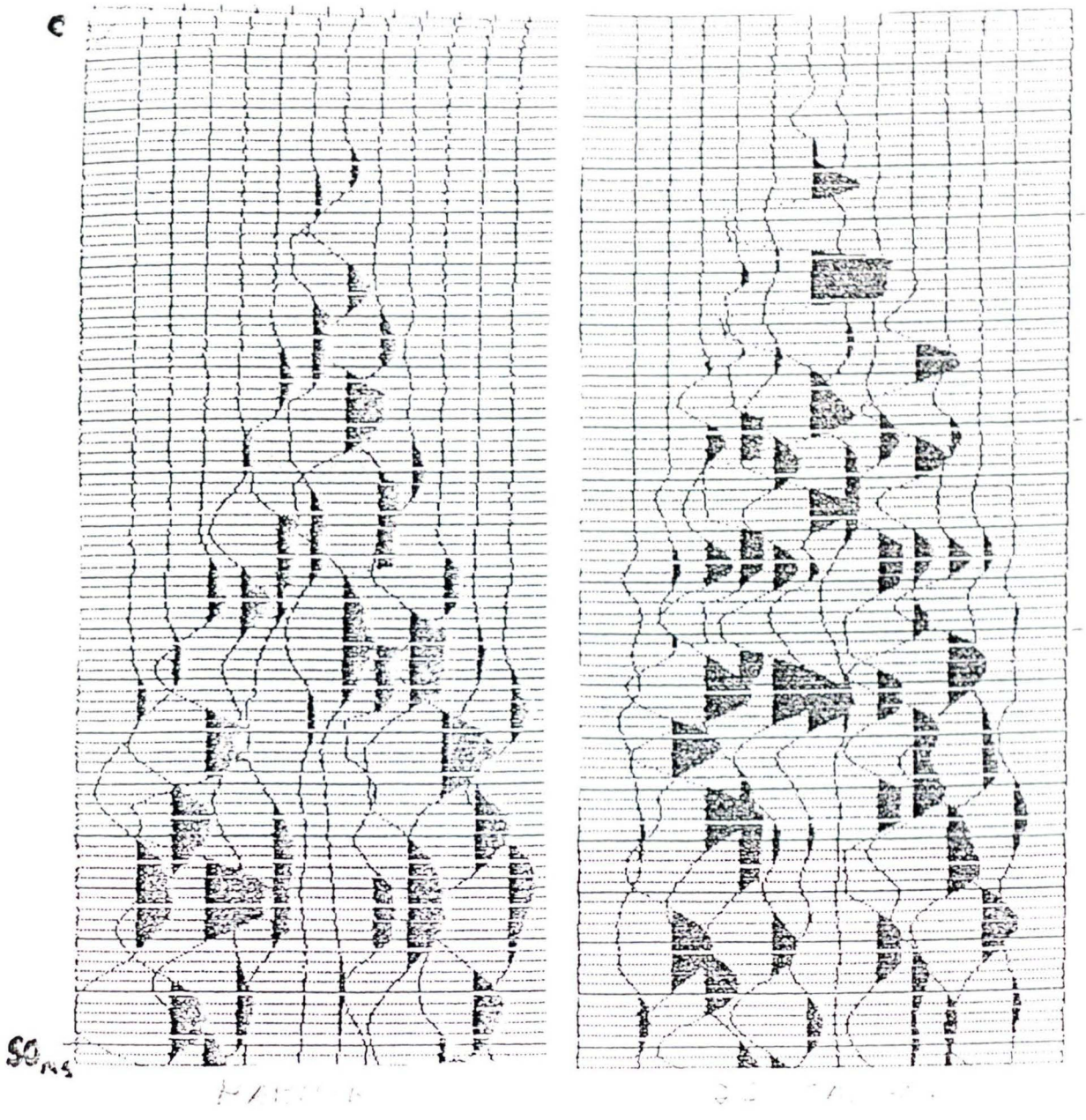
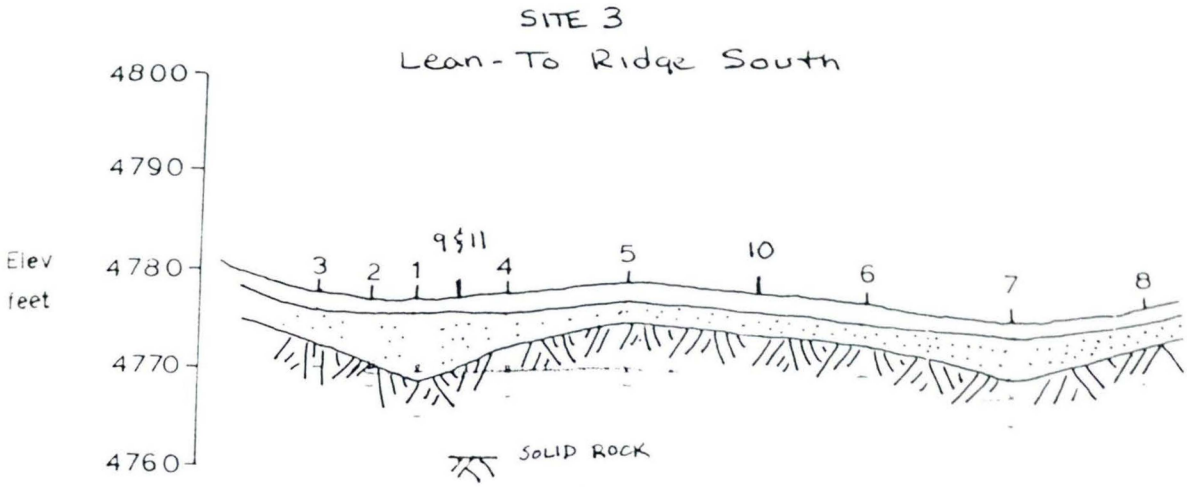


Figure 42. Comparison of Hammer Source with 22 Caliber Source.



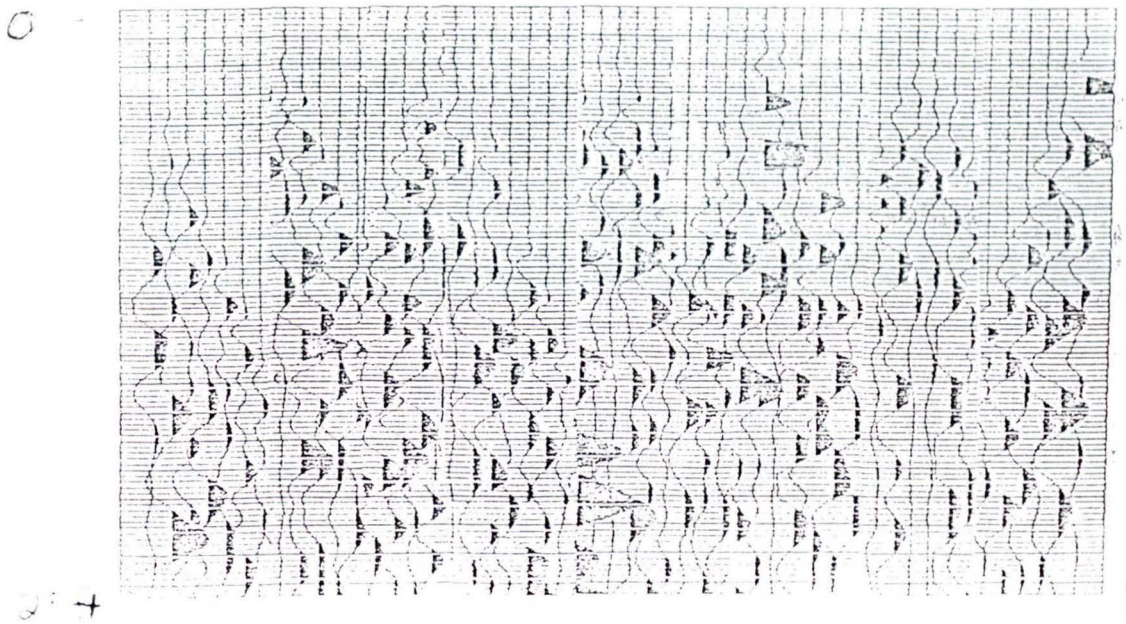


Figure 43. Reflection section at Site 3, W-E line.

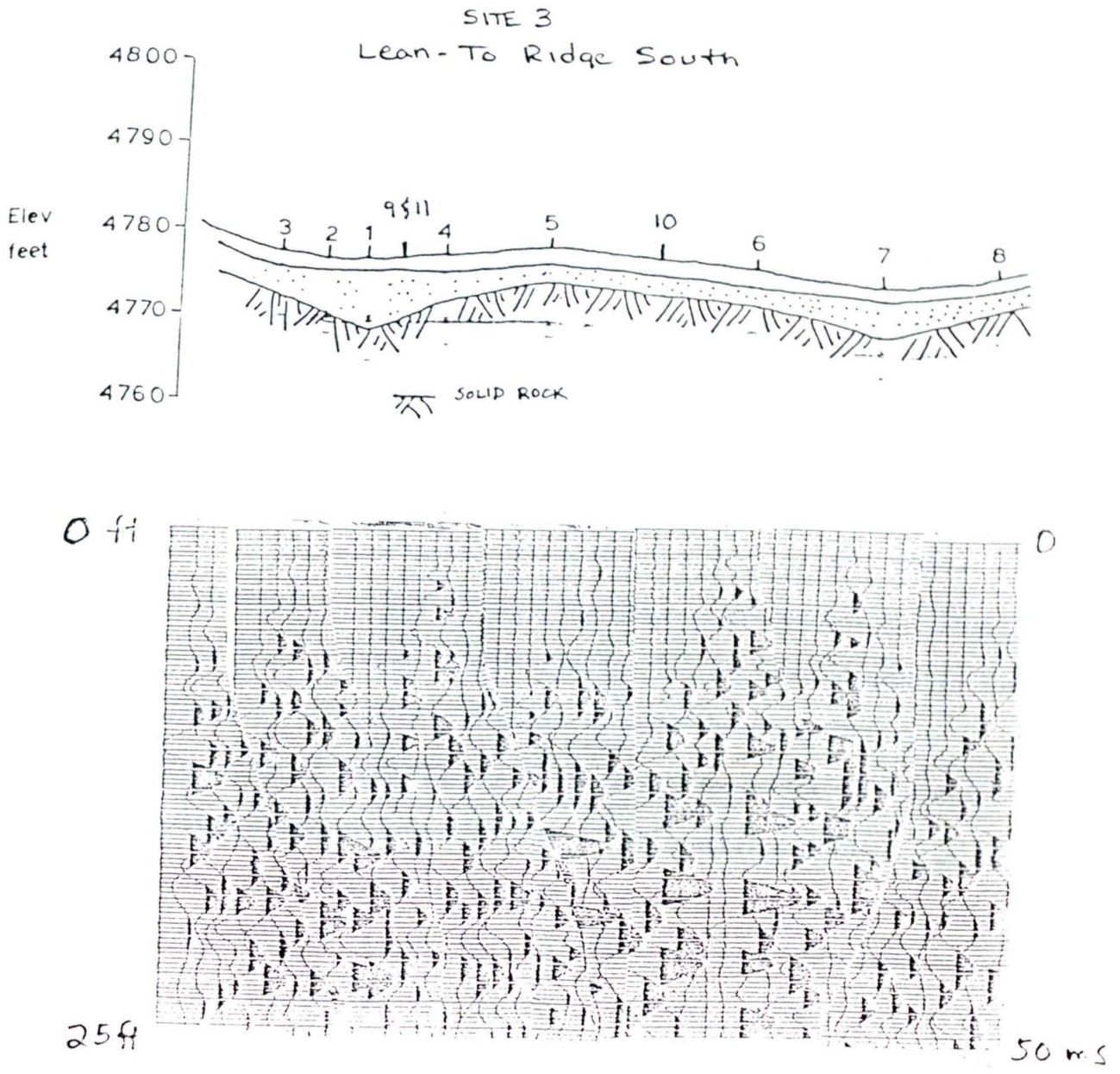


Figure 44. Reflection section at Site 3, NW-SE line.

DOWN HOLE SEISMIC METHOD

BASIC PRINCIPLES

Seismic surveys can be performed in boreholes to provide direct information on subsurface seismic velocities. We constructed a down hole geophone by removing the element from a standard engineering seismograph geophone, and mounting it in a waterproof PVC cylinder that could be lowered into the test holes. Connection to the surface seismograph was by a waterproof cable. To measure down hole times, a hammer source was employed at the top of the holes.

To help interpret the down-hole seismic data from the test sites, a method to interpret the results was required. BASIC Program MISC9 listed in the appendix determines interval velocities from borehole seismic wave surveys. It can be used for both compressional and shear wave surveys with a constant or variable spacing of the geophone in the borehole. Applications of this program to engineering geophysics include using interval velocities of both wave type to calculate elastic constants, using interval velocities in seismic stratigraphic interpretation, using a velocity column to develop characteristic site period, using interval velocities to identify hidden layers and blind zones in seismic refraction studies, using interval velocities for input to computer analysis for seismic design, using interval velocities to develop synthetic seismograms.

TEST SITE RESULTS

Down hole seismic surveys were performed at Sites 1 and 3. The resulting travel times are plotted versus geophone depth in Figures 45 and 46. The average overburden velocity at Site 1 was found to be 1070 ft/s; at Site 3, 1133 ft/s. These values are completely in accordance with the surface seismic results at these sites.

DISCUSSION

The soil velocities obtained by the down hole seismic surveys at the test sites help validate the seismic refraction interpretation discussed earlier in this report. In particular, no evidence was found of an increase in seismic velocity at the colluvium-residual soil interface.

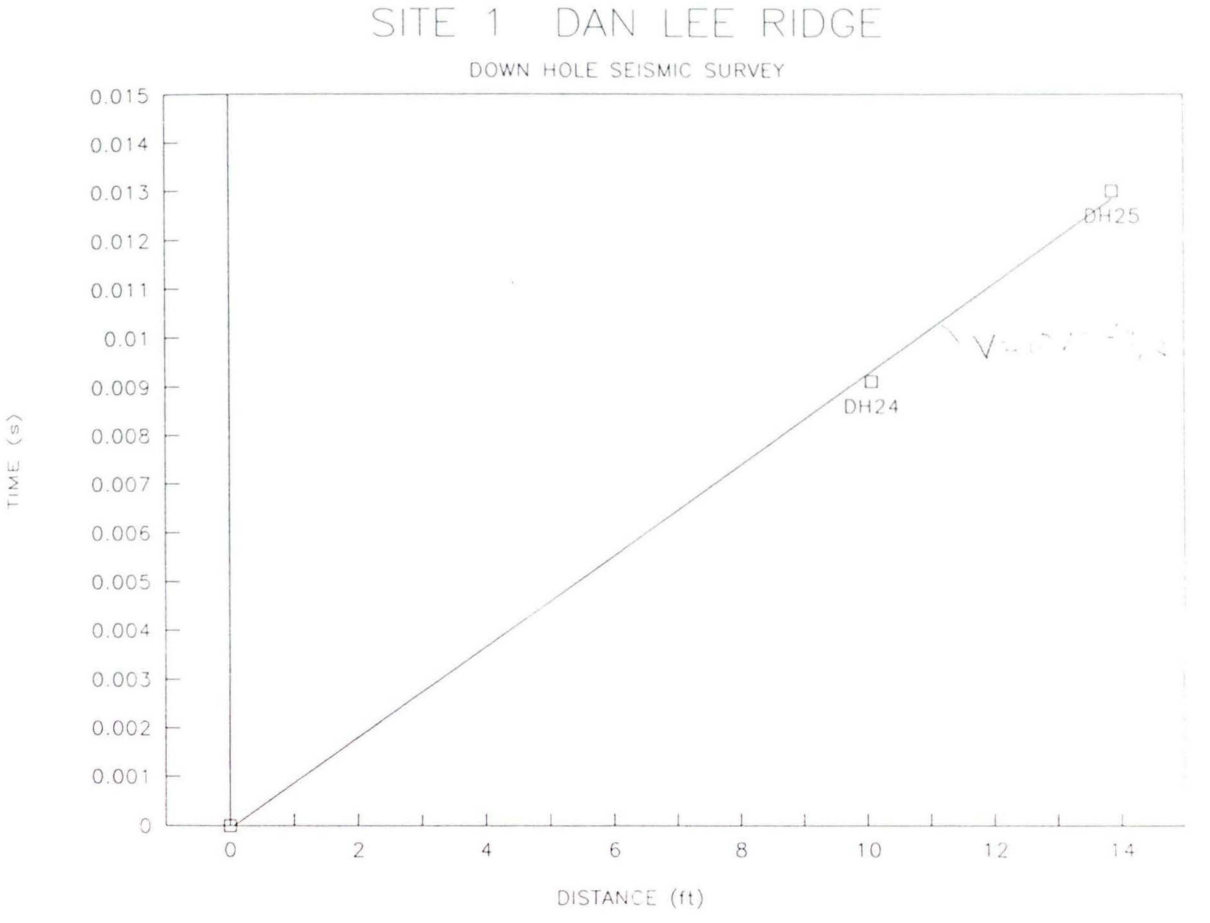


Figure 45. Down hole seismic results at Site 1.

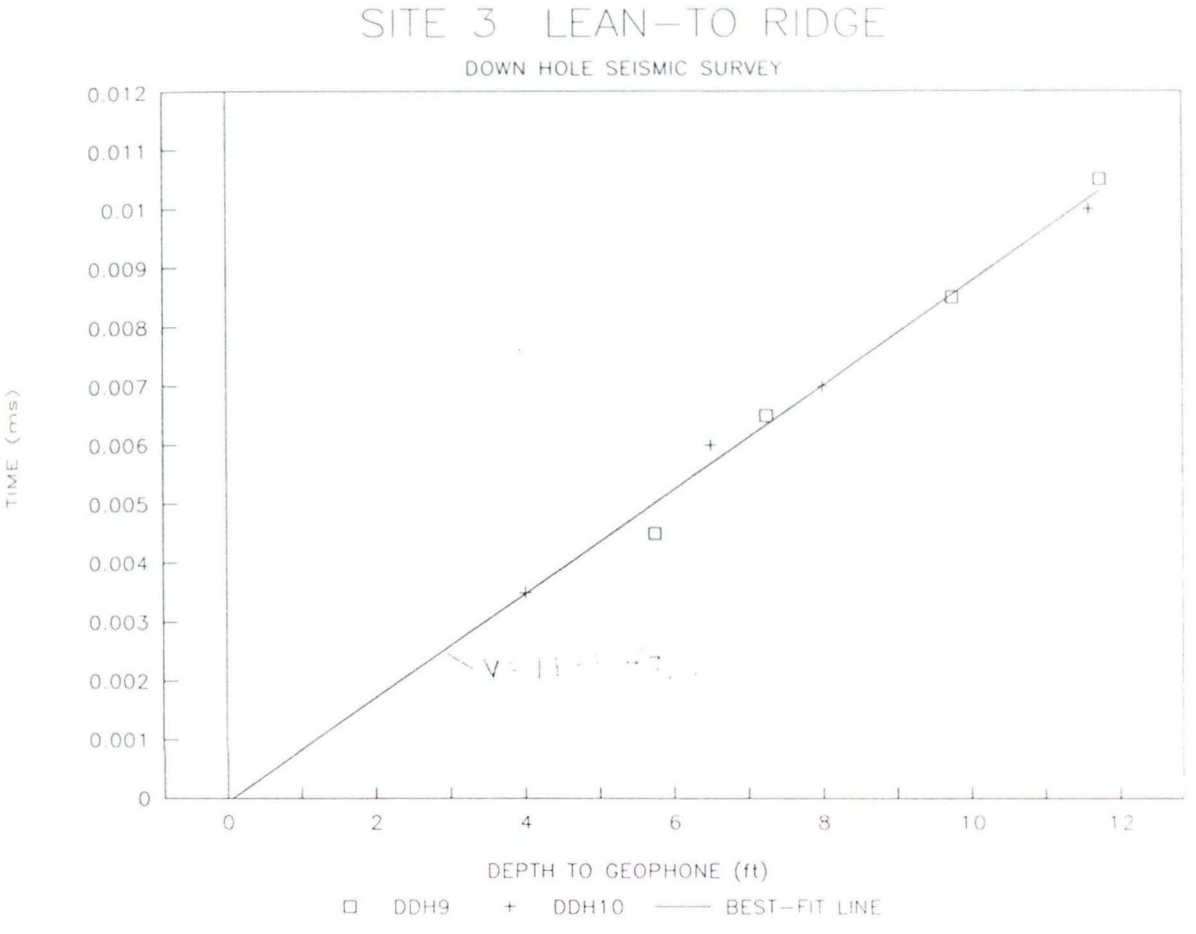


Figure 46. Down hole seismic results at Site 3.

ELECTRICAL RESISTIVITY METHOD

BASIC PRINCIPLES

Conventional ground resistivity measurements are made by applying a DC or low frequency AC current to two electrodes while measuring the potential difference between two different electrodes. In most rocks and soils, electricity is conducted electrolytically through the fluid-filling fractures and pore spaces. Thus, the resistivity of the material is controlled by the water content and water salinity rather than by actual rock material.

By using many electrodes and a microprocessor to coordinate current flows, measure potentials, correct for polarization due to the electrodes, calculate apparent resistivities, and plot the data, high resolution resistivity cross-sections can be obtained quickly in the field (Lahabi and Sprenke, 1983). Such a system also allows an evaluation of electrical noise errors by repeating the resistivity measurements many times, enabling a calculation of mean and variance of resistivity.

Geophysical measurements are fairly easy for non-specialists to understand because the method deals with the familiar Ohm's Law $V = I R$, where V is voltage, I is current, and R is electrical resistance. In three-dimensions, this law must be generalized to relate voltage and current measurements to a fundamental property of a material: resistivity. Resistivity is a bulk property of a material and, as such, is independent of geometry. The physical unit of

resistivity is the ohm-m. The inverse of resistivity is called conductivity. Conductivity is measured in units called milli-Siemens per meter.

When a DC current flows through the ground, the current must be conducted either by electronic or electrolytic means. Electronic conduction is important in metallic-lustre minerals such as graphite, pyrrhotite, and pyrite. For most rocks, on the other hand, the rock matrix is more of an insulator than a conductor, and electrolytic conduction is by far the more important mechanism.

The ions in the water within the pores of a rock come from the disassociation of salts within the groundwater. The relationship and the petrophysical properties of rock are expressed in an empirical relation known as Archie's Law:

$$R = A \frac{Rw}{Sw^2 \ \Phi^2}$$

where R is the resistivity of the rock, Rw is the resistivity of the contained water, Φ is the porosity, and Sw is water saturation. A is an empirically derived constant. The presence of clay minerals within a rock type or soil tends to decrease the materials resistivity for a number of reasons. The clay minerals tend to ionize and contribute to the supply of free ions. They can combine with water. They can absorb cations in an exchangeable state on their surfaces. Clay bearing rocks and soils tend to have less resistivity than sandy or silty soils.

In general, resistivity tends to increase with particle size in a rock or soil. As pointed out above, clays and argillaceous materials tend to have very low resistivities; silt tends to be intermediate in resistivity; sands and gravels tend to be higher. Dense rock types tend to have very high resistivities.

A soil or rock showing resistivity less than 100 ohm-m is said to possess low resistivity; from 100 to 1000 ohm-m, intermediate resistivity; greater than 1000 ohm-m, high resistivity. In general, wet soils tend to have resistivities from 100 to 500 ohm-m. In arid regions, soils can have resistivities up to 1000 ohm-m.

Saturated sediments have resistivities from 1 to 100 ohm-m; unsaturated sediments, 10 to 1000 ohm-m; igneous and metamorphic rocks, from 100 to 10000 ohm-m, depending on their porosity. Metallic ores have very low resistivities down to 0.00001 ohm-m. Non-metallic ores, such as evaporites, can have resistivities as high as 1,000,000 ohm-m.

The resistivity of water depends on its ionic content. Water with less than 5 ppm of total dissolved solids has a resistivity of over 1000 ohm-m, with 100 ppm, about 100 ohm-m, and with 500 ppm, about 12 ohm-m at standard conditions. Generally, water is considered potable if its resistivity is higher than about 10 ohm-m. Water in soil tends to vary from 1 to 1000 ohm-m; rain tends to be more resistive, 30 to 1000 ohm-m; sea water, being very saline, drops down to the order of 0.1 to 0.2 ohm-m. Ice, on the other hand, is very resistive with a resistivity of at least 10000 ohm-m.

The electrical resistivity method is generally used in one of two modes. The first method--electric sounding-- is used to find the depth to subsurface boundaries separating layers of different resistivities. For example, it might be used to find the depth to the water table because the resistivity of soil tends to change abruptly at the water table surface. The major problem with this method is that it requires the existence of two horizontal and homogeneous media. In many localities, the water table may be inclined or even undulating, thus voiding the basic premise of the sounding method. Localized channels of groundwater flow would also be inappropriate for sounding investigation.

BASIC Program RIP4 in the appendix computes theoretical vertical electrical sounding curves for the Schlumberger and Wenner electrode arrays. The earth structure must be a horizontally layered medium consisting of up to nine layers over a halfspace. The input consists of layer thicknesses, resistivities, and array geometry. The output consists of electrode spacing-apparent resistivity pairs sampled at six points per decade of electrode spacing. For the Schlumberger array, the electrode spacing is AB/2; for the Wenner array, it is AB/3, where AB is the distance between outside current electrodes. The user enters the minimum and maximum electrode spacings to be calculated. The units used are m and ohm-m. This program calculates resistivities at six points per log cycle but only uses three points per cycle in the calculation. Hence, it may prove inadequate for computing sounding curve branches that steeply descend. The program is modified from Zhody and Campbell (MGHCP, 1981) and Haines and Campbell (MGHCP, 1981).

The second method of resistivity surveying--horizontal profiling-involves traverses across the survey area to locate subsurface materials with anomalously high or low resistivities compared to the surrounding environment. Groundwater channels, for example, because of high water content, would presumably show a lower resistivity than the surrounding unsaturated material. Changes in soil types and bedrock lithology might also be detectable by this technique. Horizontal resistivity profiling may have other applications in the National Forests as well:

1. Locating sand and gravel deposits.
2. Mapping regional variations in soil types.
3. Locating buried stream channels.
4. Mapping fault and breccia zones.
5. Locating mineral deposits.
6. Mapping archeological sites.
7. Indirectly estimating soil and rock strengths.

Compared to other geophysical methods, resistivity offers flexibility in that it can be done with short electrode spacings for shallow work or very long spacings for deeper work without changing the method of measurement. Resistivity measurements are straightforward in that simple voltage and current measurements on metallic electrodes are the basic measurement. Field expenses are minimal; the equipment is reasonably lightweight and portable for shallow engineering work.

Qualitative interpretation of resistivity profiles is straightforward. One simply looks for areas of relatively high or low resistivities. Offsetting this simplicity are some limitations. The

interpretation, being qualitative, may not be useful. It may, for example, be impossible to discriminate between a resistivity low due to a groundwater channel as opposed to a change in soil type. The accuracy of quantitative resistivity work is substantially lower than seismic techniques.

Probably, the most important factor to consider when comparing resistivity and seismic surveys is that resistivity responds to completely different factors than the seismic method. Resistivity responds to water content and the salinity of the contained water in the material. Where these factors can be interpreted in terms of the local geology, the resistivity method has an important role to play, particularly if groundwater is of interest. Resistivity surveys, if run in combination with seismic methods, present a powerful tool for understanding the subsurface environment at engineering sites. This is particularly the case if some drill hole information is available for control purposes.

For resistivity profiling, the location of the entire electrode array is changed between readings, but the spacing between electrodes is held fixed. The depth of investigation, being dependent on electrode spacing, remains the same from one reading to the next. Resistivity profiling results show lateral changes in resistivity. Figure 47 shows the basic resistivity setup using equally spaced electrodes. This is used in the so-called dipole-dipole mode with two current electrodes on one side of the array and two potential electrodes on the other side. A similar array, the Wenner Array could be used with similar results.

Equipment for resistivity must be capable of measuring current and voltage with a precision of several percent which is easily achievable with conventional electronic circuits. The readings must be free from error due to electrode polarization. This can be accomplished by reversing the flow of current periodically or by using nonpolarizing electrodes. One of the biggest sources of error is current leakage through poorly insulated cables. Electrode resistance can be a problem. Some steps can be taken to overcome this problem. The metal electrode stakes can be driven down until a moist soil layer is encountered. In our national forest sites, this became more difficult as the soil dried during the summer months; but even at the driest seasons, moisture was found within a foot of the surface. If electrode contact becomes a problem, several electrodes can be used or the electrodes can be watered. For the small scale experiments performed in shallow soil environments for this study, the latter remedy was avoided for fear of interfering with the natural groundwater environment.

To decide on the electrode spacing, a rule of thumb is to take the depth in which one is interested in investigating, and multiplying by a factor of two. If 5 ft of investigation is desired, then electrodes should be 10 ft apart. This is not a hard and fast rule. It can be adjusted for local conditions. An orientation survey should always be performed prior to a profiling survey by performing an expanding electrode sounding to obtain some idea of the sensitive depths in so far as geologic and hydrologic structure in the area are concerned.

To obtain the apparent resistivity of the ground from a resistance reading, standard formulas can be applied which depend on the type of

array used and the distance between the electrodes (Figure 47). BASIC Program RIP1 in the appendix performs this calculation for resistivity surveys using the Wenner, Schlumberger, dipole-dipole, rectangular bipole-dipole, or general arrays.

The field data, after being converted to apparent resistivity, is generally plotted on what is referred to as a pseudo-cross section. The center point of the array, at which each measurement is taken, is the plotting point in the horizontal direction. On the vertical scale, the point is plotted at the electrode spacing. Shallower readings, that is, shorter electrode spacings, are placed near the top of the plot whereas deeper readings are plotted toward the bottom. These sections, in appearance similar to geologic cross-sections, are convenient for interpretation.

TEST SITE RESULTS

Resistivity measurements were made at Sites 1 and 3. Resistivity profiling serves to detect lateral changes in resistivity. Successive measurements at different locations results in a sampling of earth resistivity along the survey line. The dipole-dipole array was used in this study. This array is commonly used in the mining industry. At the National Forest sites, the target depths (Water table, bedrock, soil horizons) were 5 ft to 20 ft thick. Hence, an electrode spacing of 5 ft was used to ensure a high resolution profile at the site. In some cases, profiles were run at several different spacings in order to construct pseudo-cross-sections of the subsurface environment.

On pseudo-cross sections, the boundaries between different lithological or hydrological units may be mapped by inspection of the profile results. If the subsurface units do not possess a resistivity contrast with the surrounding units, then they will not appear on the pseudo-cross-sections.

Site 3 Down Hole Resistivity

A down-hole resistivity measuring device was especially developed for this study in the University of Idaho Geotechnical Laboratory. Three equally spaced copper electrodes separated by 6 " were lowered into Borehole #2 (1984) at Site 3 in 1984. This borehole extended below the water table and all three electrodes were in contact with natural groundwater--a condition which served to provide an electrical contact between the measuring electrodes and the downhole borehole environment. The resistance was measured with an ABEM Terrameter to be 1000 ohms +/- 200 ohms. The standard equation relating resistance to true rock resistivity for a vertical electrode array composed of 4 equi-spaced electrodes is $R = 4 \pi a r$, where R is resistivity, a is the electrode spacing, and r is resistance. This equation yields a value of 1900+/-400 ohm-m for the resistivity of the unconsolidated sediments below the water table at Site 3. This value seems high compared to the range given by Mooney (1980) for saturated unconsolidated sediments (1 to 100 ohm-m). The high resistivity obtained at Site 3 is probably the result of low ionic content in the groundwater--a condition typical of high mountain sites in granitic terrain in central Idaho. An unfortunate consequence is that little resistivity contrasts exists between the unconsolidated material below the water table and either the

unsaturated material above or the dense bedrock below. Near surface resistivities at Site 3 are also of the order of several thousand ohm-meters. Without a large resistivity contrast at the water table, the resistivity method fails to detect the water table surface.

Sites 1 and 3 Profiling Results

Resistivity pseudosections for Site 1 and Site 3 are shown in Figures 48 and 49. Generally, it is difficult to correlate the results to the geology as known from the drill holes. In particular, the resistivity lows do not correlate with the known water channels in the subsurface. In fact, the channels appear to correlate best with resistivity highs.

The change in resistivity with seasonal variations in groundwater levels was an important parameter to study. Figures 50 to 58 show these data at Site 3. Very spectacular seasonal changes in apparent resistivity occur. This indicates that resistivity measurements are very sensitive to changes in soil moisture.

DISCUSSION

The resistivity method is potentially a very powerful means to study water content in the shallow subsurface. However, the data are not easy to interpret. More study of this method is required before it could be used routinely to locate zones of ground water concentration.

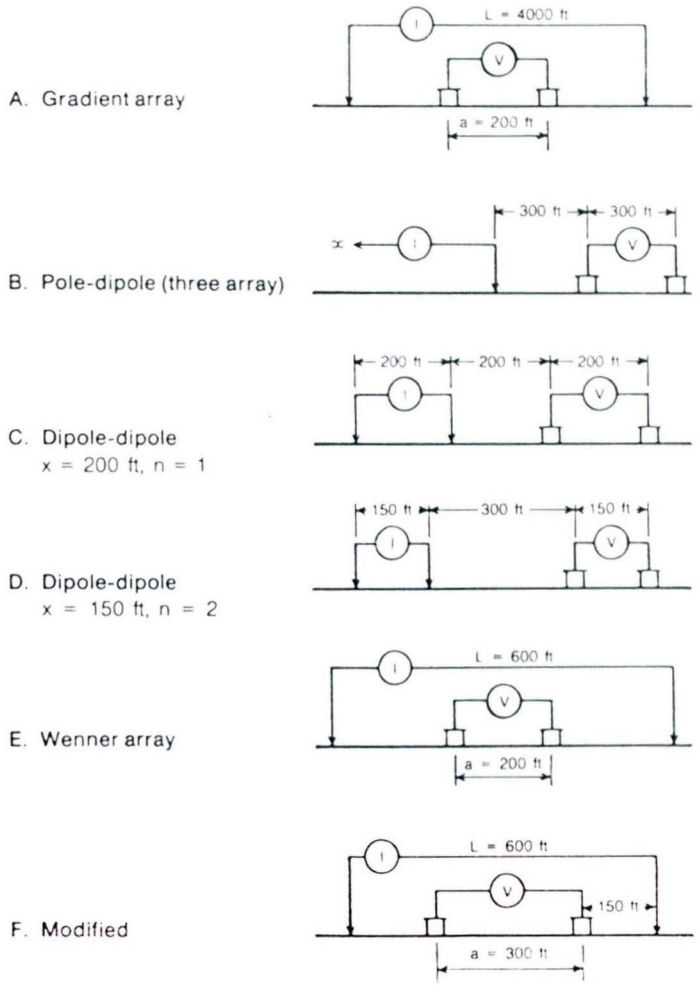


Figure 47. The basic resistivity field layout for a resistivity survey.

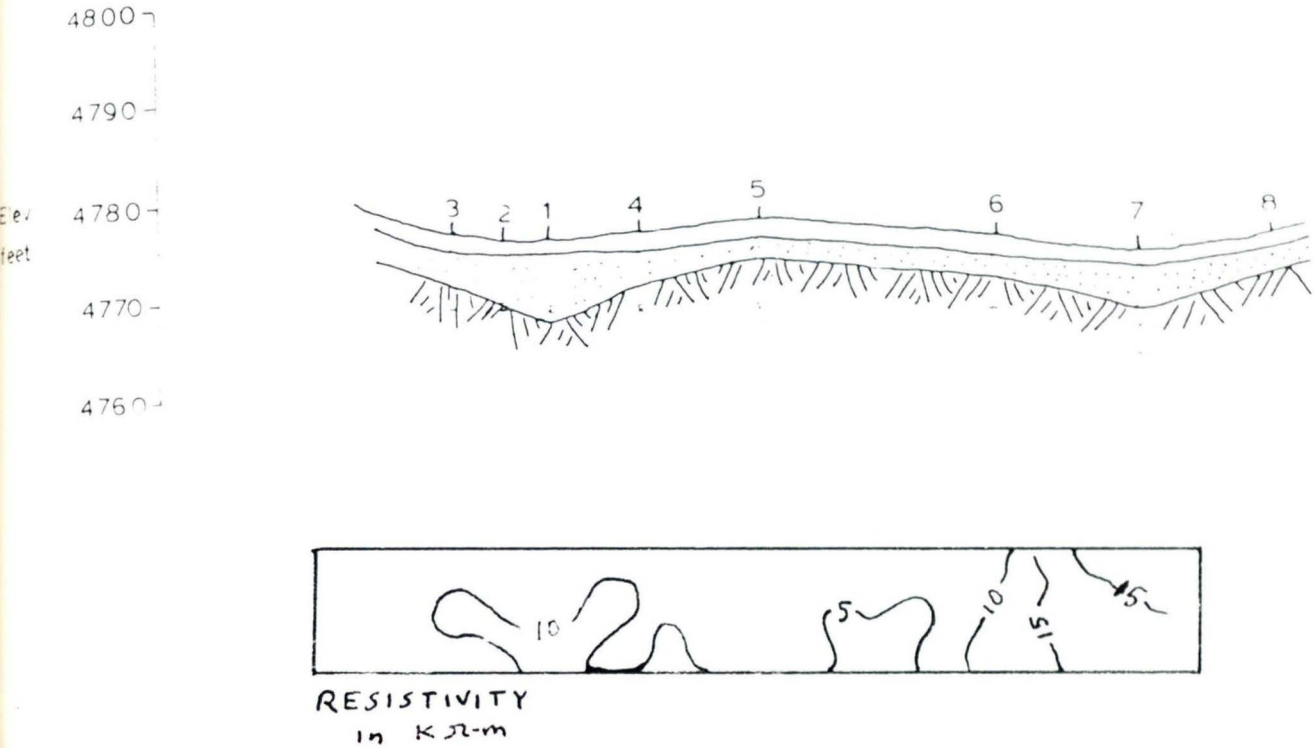
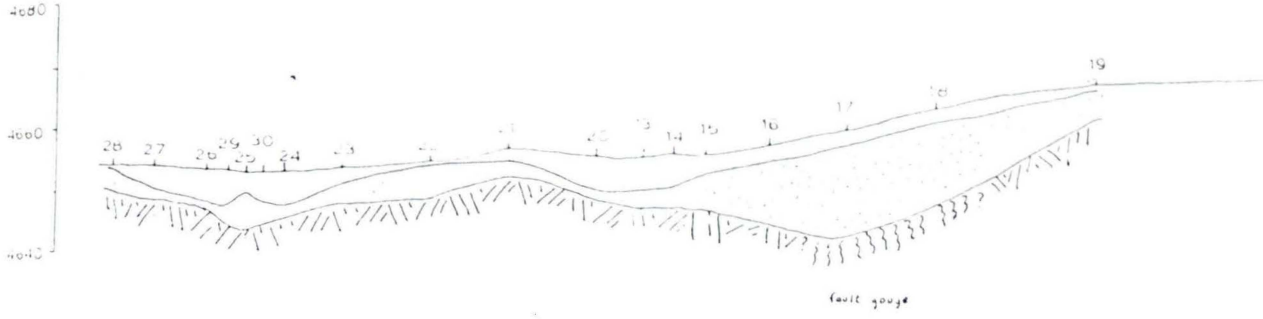


Figure 48. Resistivity pseudo-section at the Lean-To Ridge site.



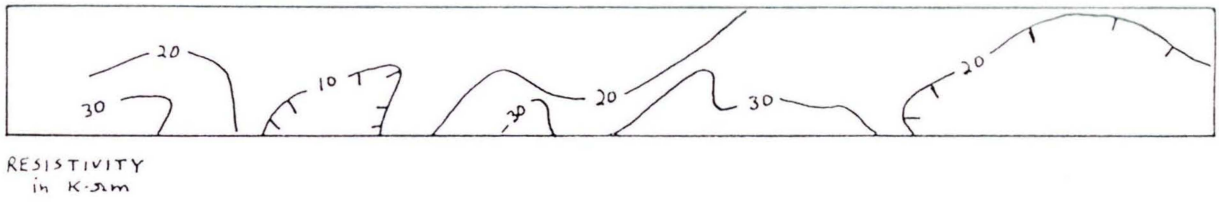


Figure 49. Resistivity pseudo-section for the Dan Lee site.

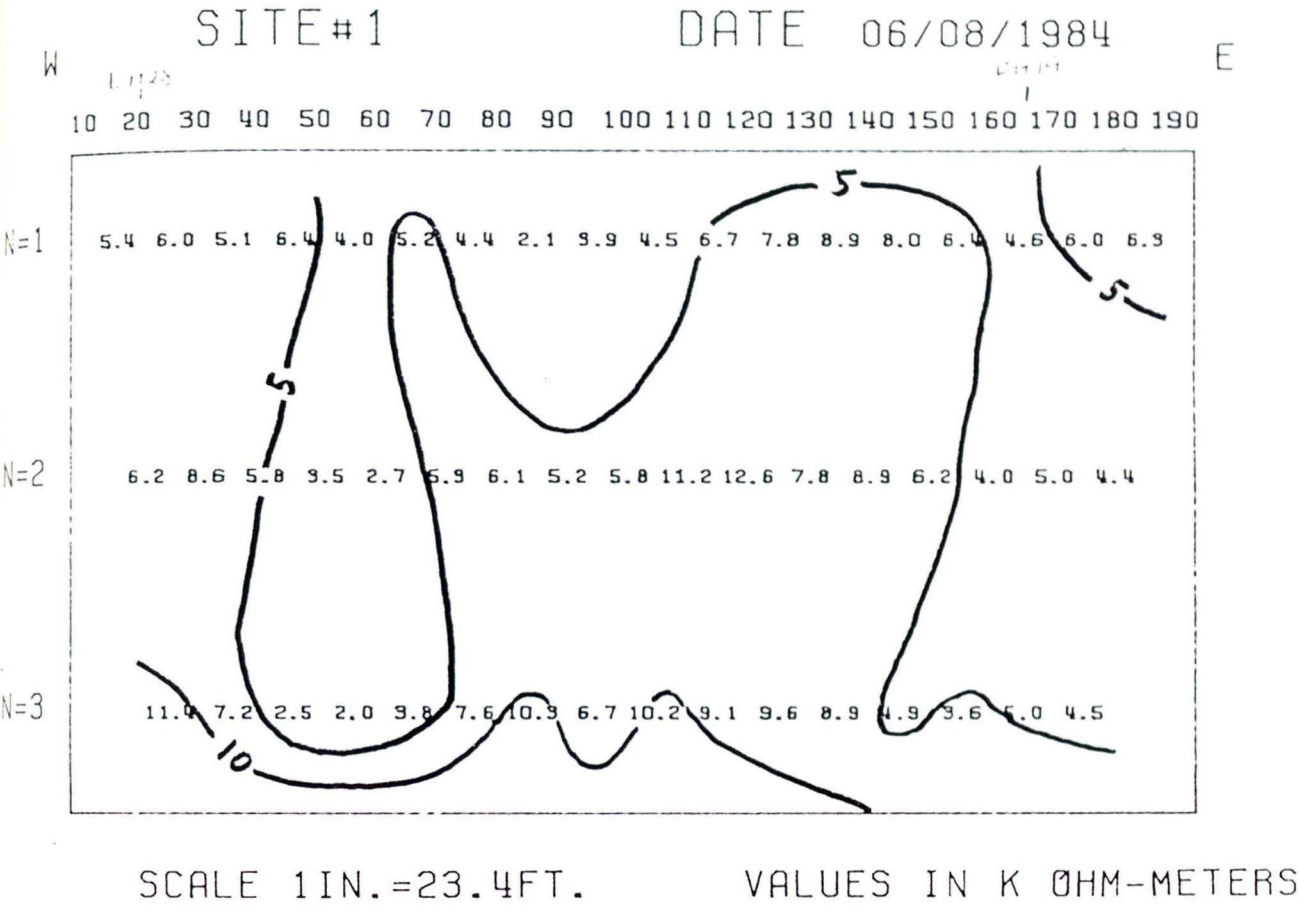


Figure 50. Apparent resistivity at the Dan Lee Ridge site, 6/8/84.

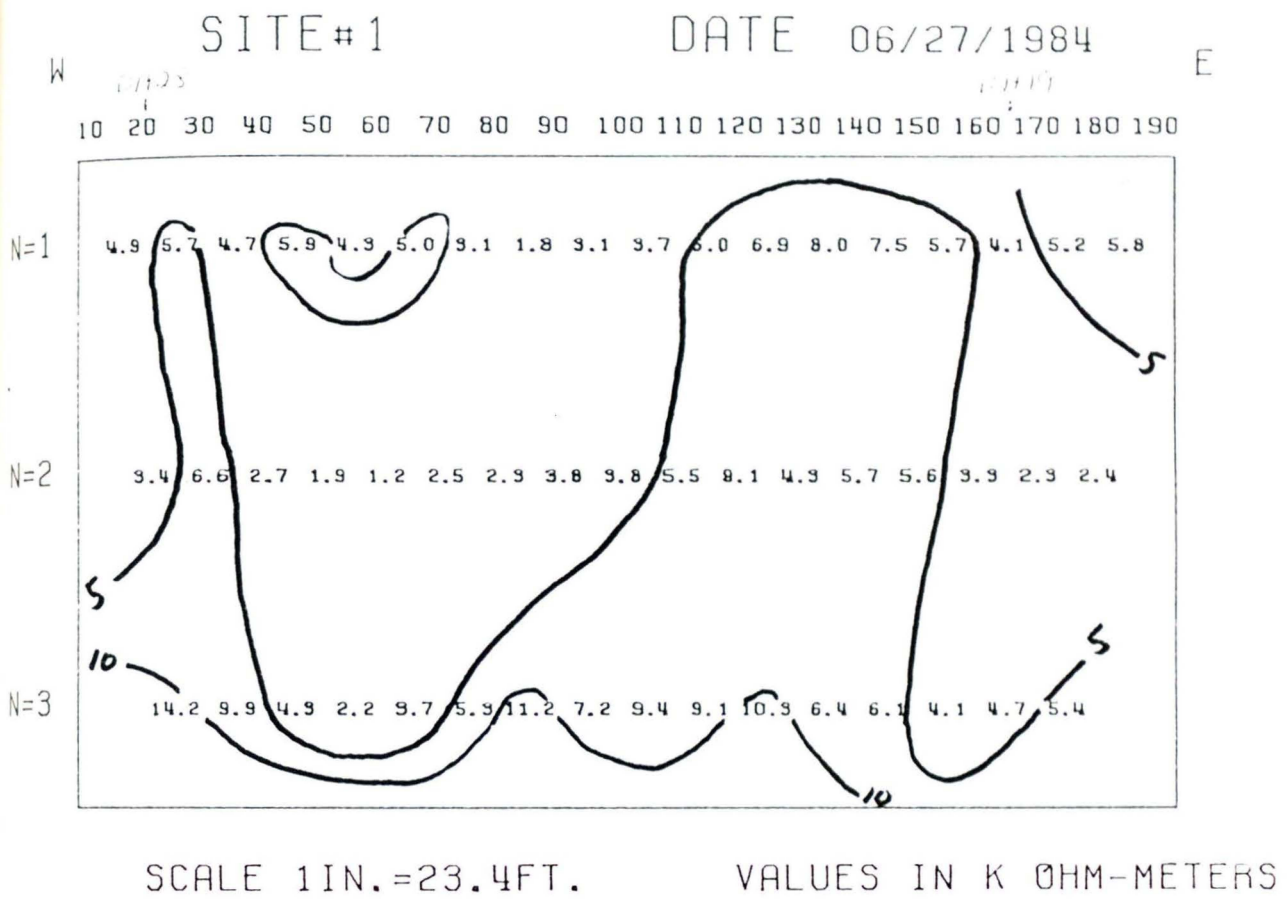


Figure 51. Apparent resistivity at the Dan Lee site, 6/27/84.

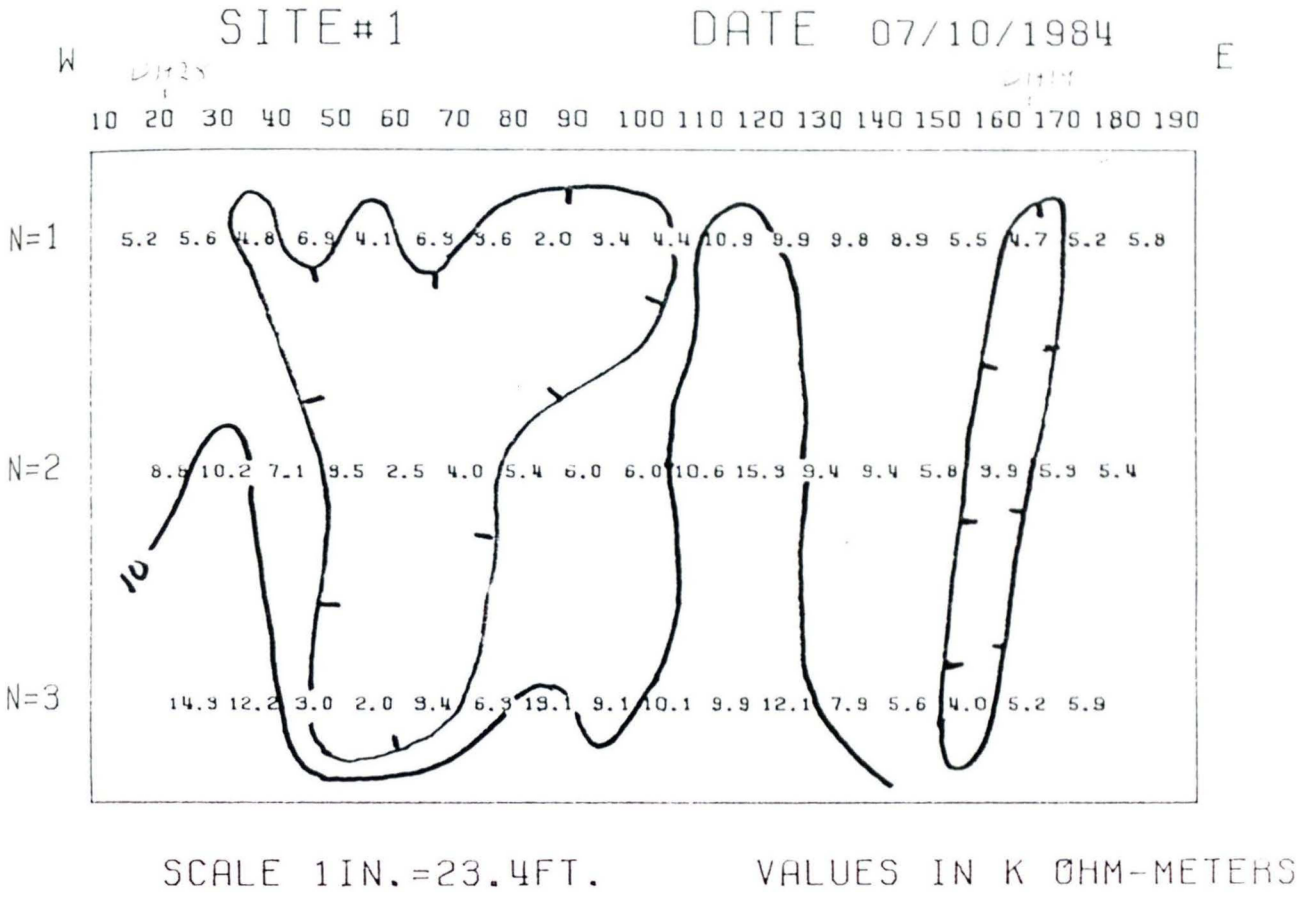


Figure 52. Apparent resistivity at the Dan Lee site, 7/10/84.

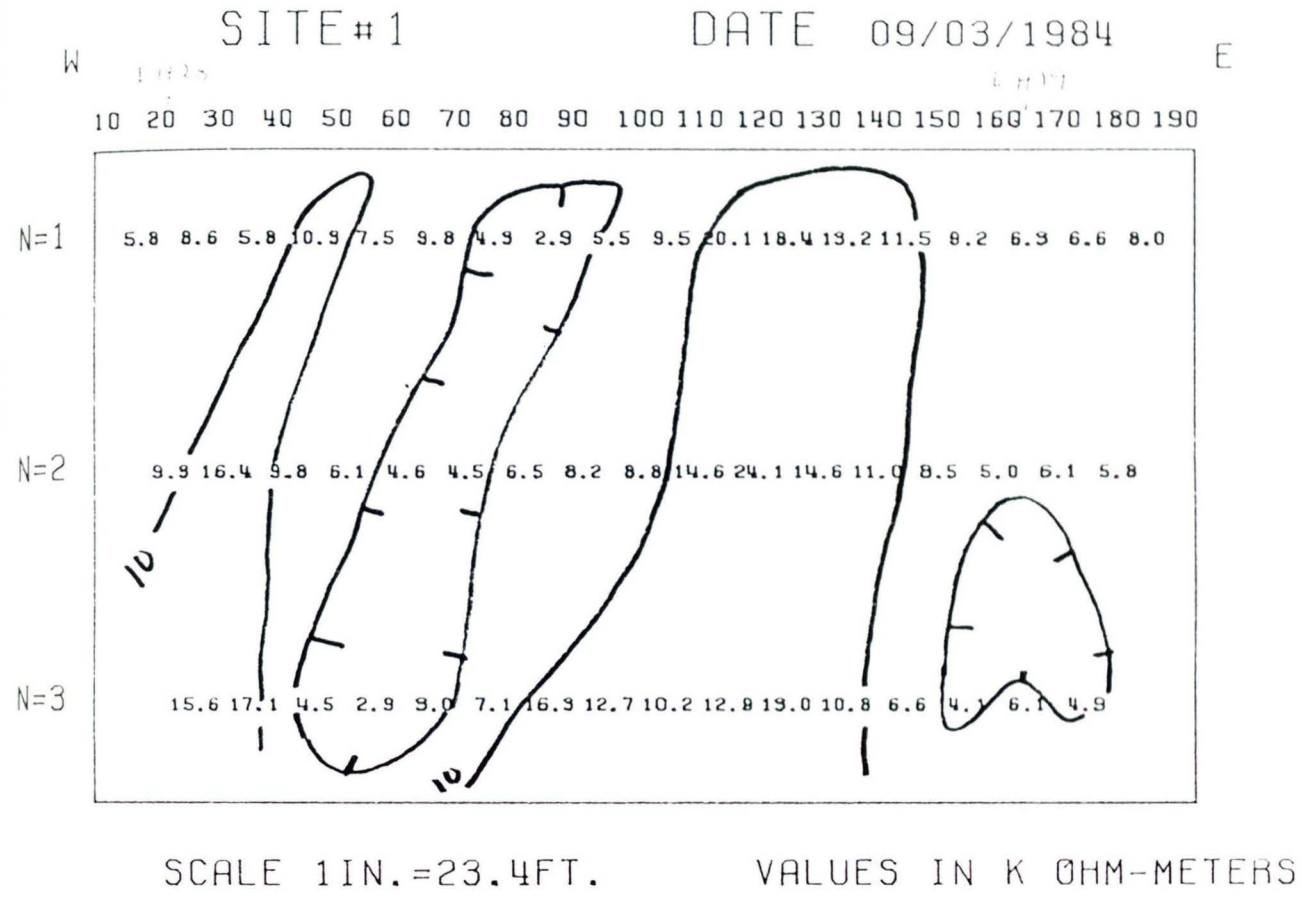


Figure 53. Apparent resistivity at the Dan Lee site, 9/3/84.

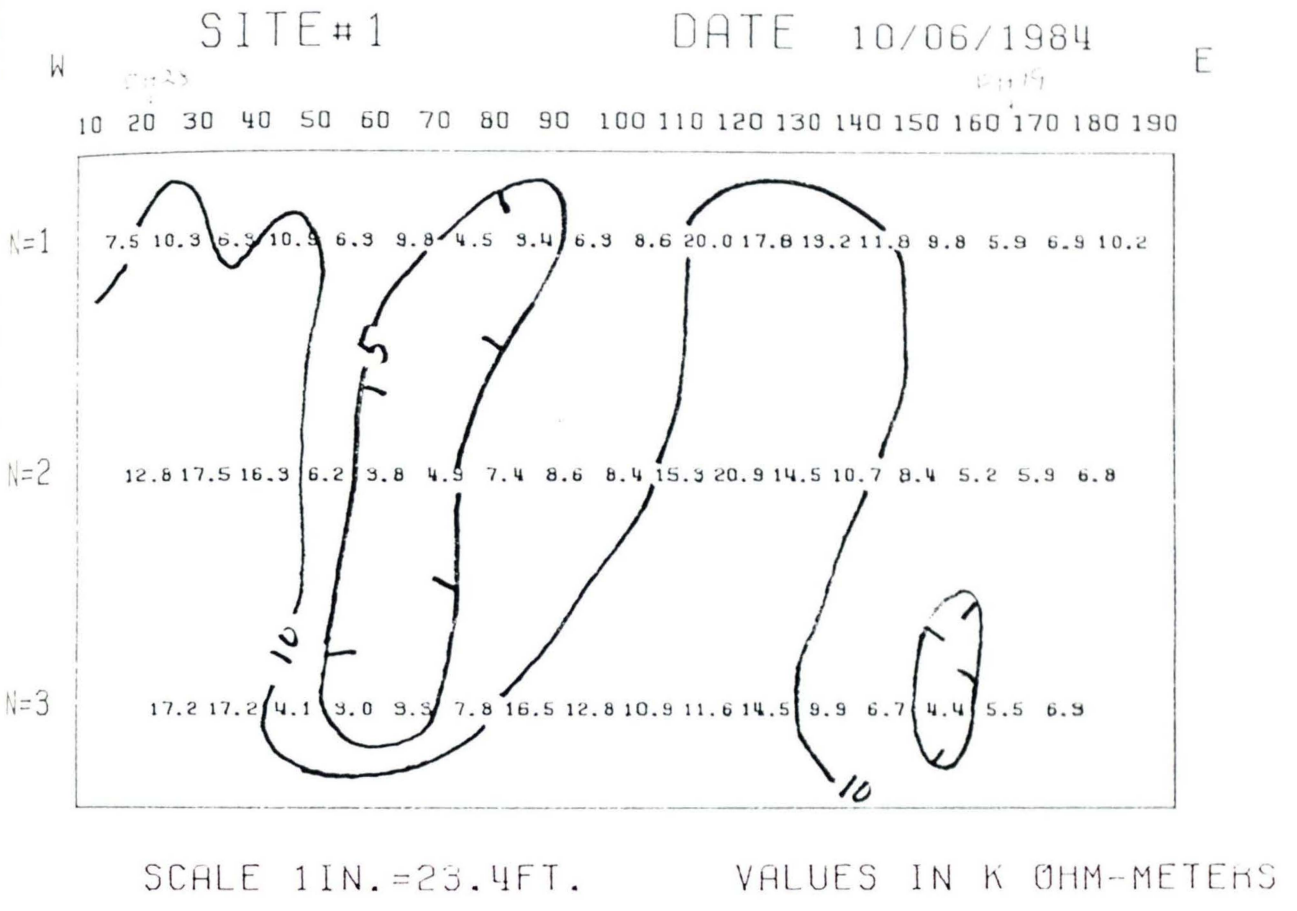


Figure 54. Apparent resistivity of the Dan Lee Ridge site, 10/6/84.

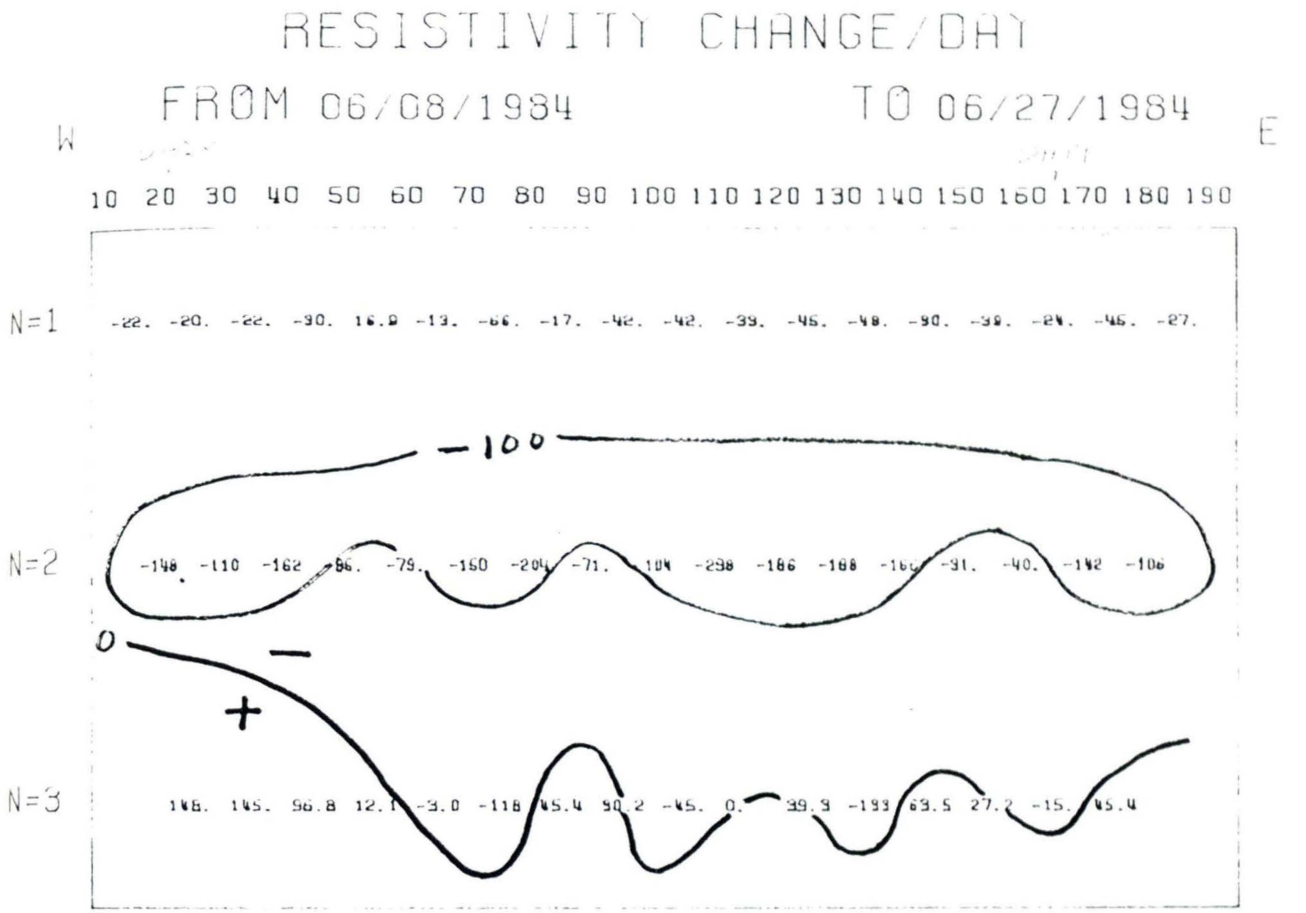


Figure 55. Change in apparent resistivity during June, 1984.

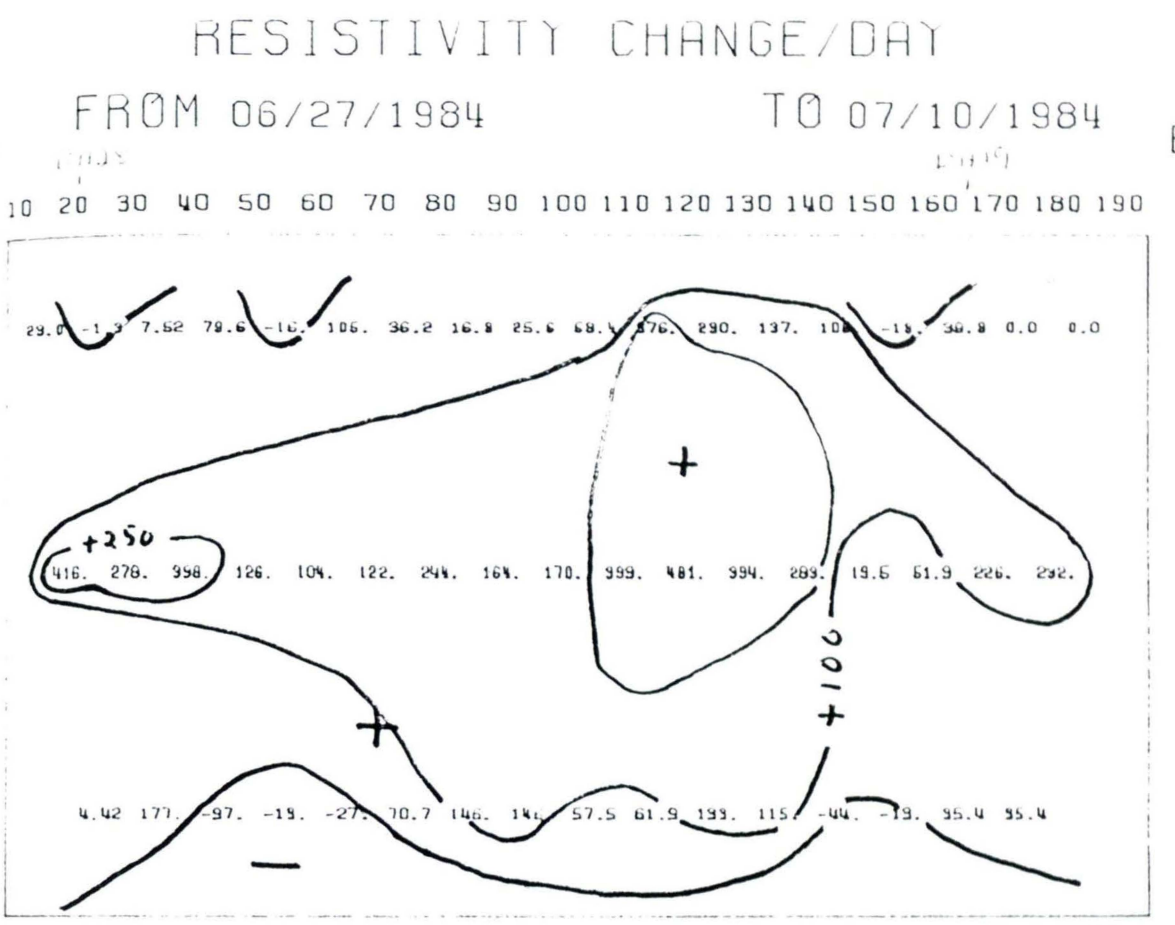


Figure 56. Change in apparent resistivity during July, 1984.

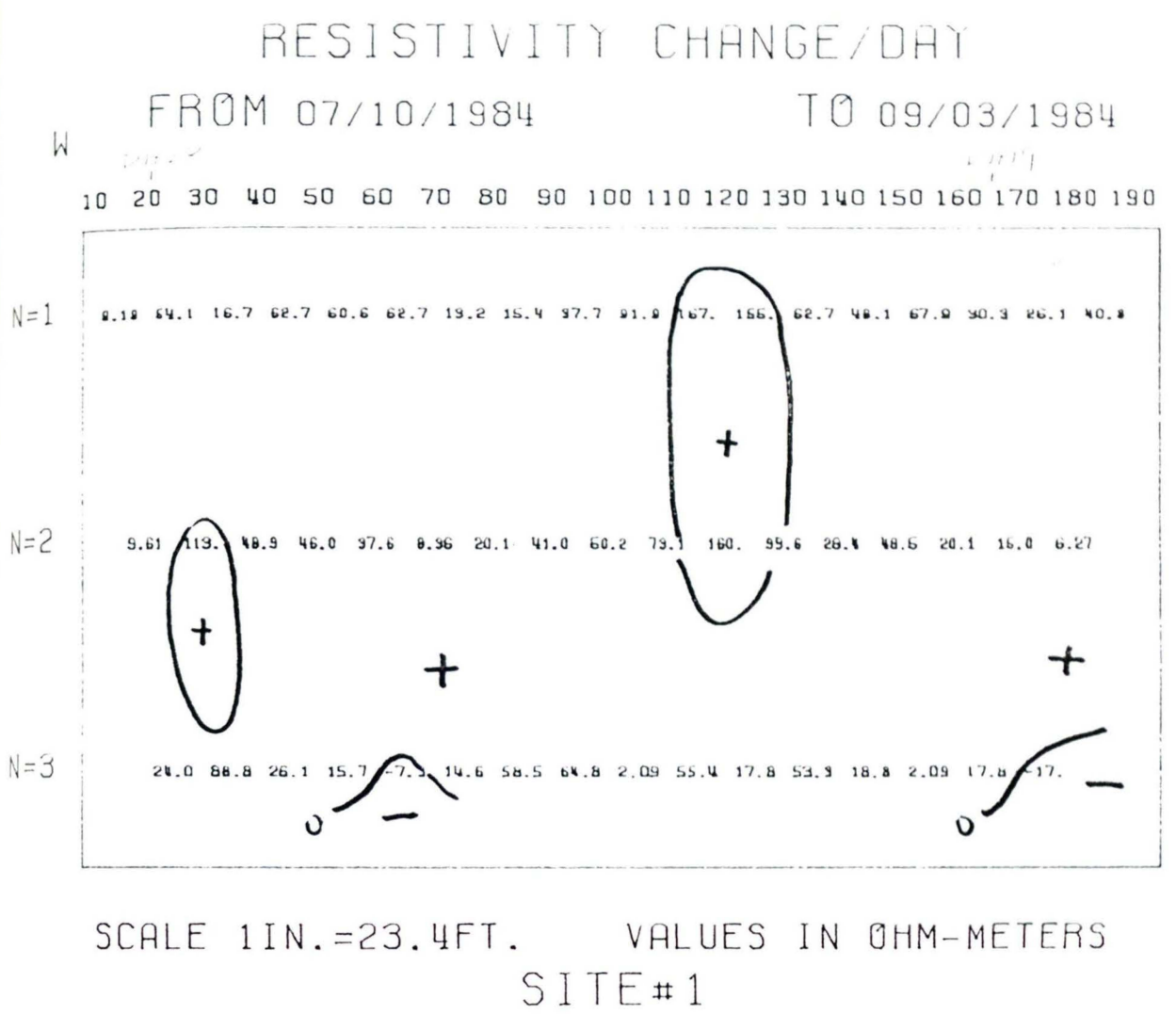


Figure 57. Change in resistivity during August, 1984.

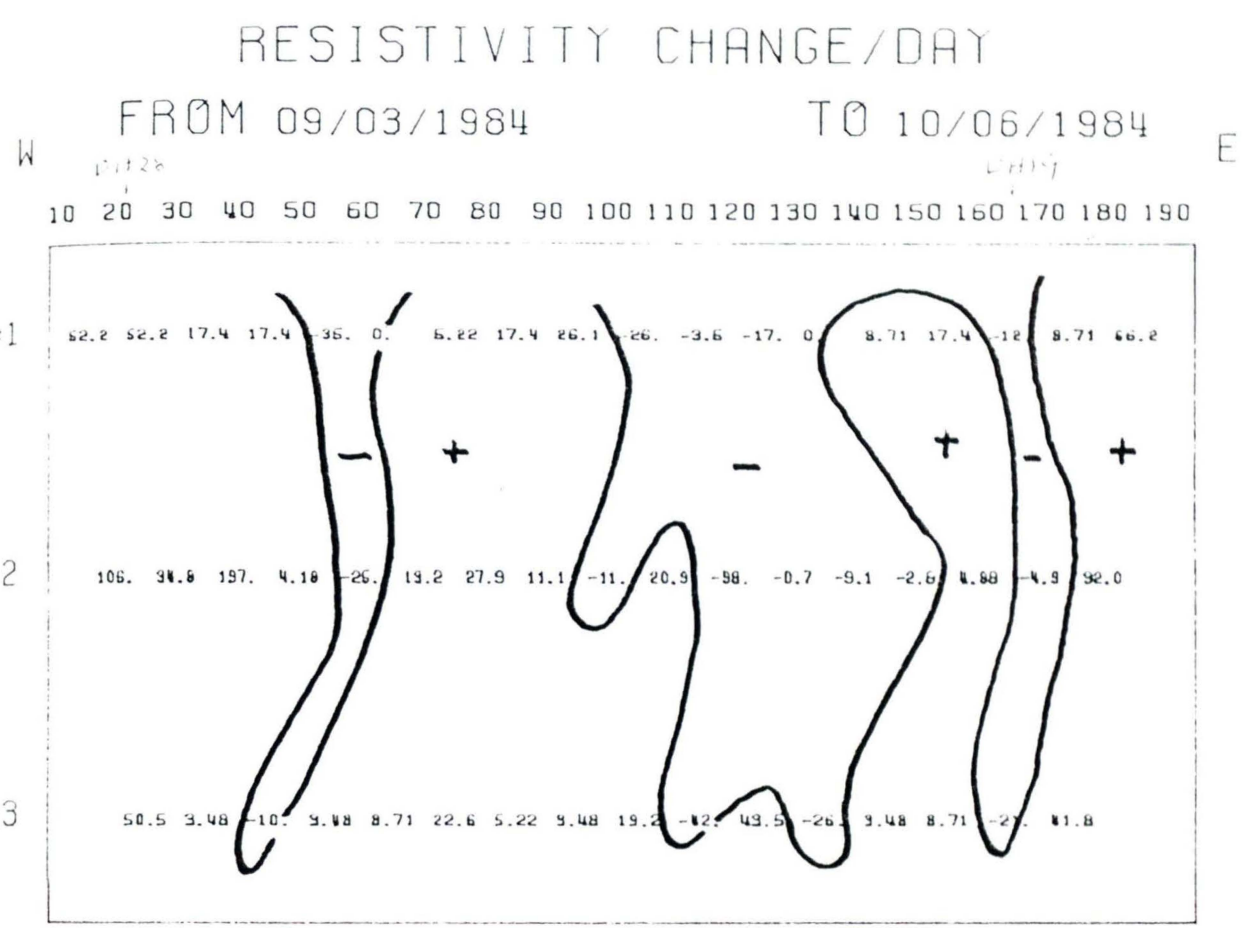


Figure 58. Change in resistivity during September, 1984.

BASIC PRINCIPLES

Natural or spontaneous potentials occur in the subsurface due to electrochemical or mechanical activity. One type of spontaneous potential--the streaming potential--develops when a solution is forced through a capillary or porous medium. This potential, which is generally less than about 100 mv, may be used to locate narrow zones of groundwater concentration and flow (Koerner and others, 1979; Zhody and others, 1974).

Self potential surveys are rapid and simple. The potential difference between two non-polarizing electrodes is measured with a high impedance DC voltmeter. Data interpretation is generally qualitative. Interpretation problems may arise from potentials generated by the bio-electric activity of plants. These potentials have been measured to be as large as several hundred millivolts (Telford and others, 1976).

BASIC Program RIP5, which is listed in the appendix, computes the self-potential (SP) anomaly due to a rectangular source along a vertical contact. The potential is computed on the surface of a halfspace at equally spaced stations along a line specified by the user. The model source voltage is produced by differences in electrokinetic coupling coefficients such as the streaming potential. This program is useful for interpretation of SP data measured near vertical contacts. For a discussion including a complete derivation, see Fitterman (Calculation of self-potential anomalies near vertical contacts, 1979, Geophysics,

44, 195-205). The program features a menu which allows input of parameters in any order. The location of the profile is specified by the coordinates of the first and last stations. Any station increment can be specified. The profile can be oriented at any azimuth relative to the strike of the model.

TEST SITE RESULTS

Figures 59 and 60 show profiles of SP measured at Site 1 and Site 3 with site geology. Though definite SP anomalies occur, no clear correspondence with subsurface water concentrations seems to exist. In addition, we found that the SP anomalies changed drastically from season to season. We also found the readings to be unstable with respect to how the non-polarizing electrodes were placed in contact with the ground. For example, if the electrode locations were watered before the electrode was placed, very different SP results were obtained.

DISCUSSION

The self-potential method does not seem to be very useful for detection of ground water concentrations in gruss-covered terrain of central Idaho. The dry environment makes it very difficult to obtain good electrical contact with the ground and the readings do not tend to be repeatable.

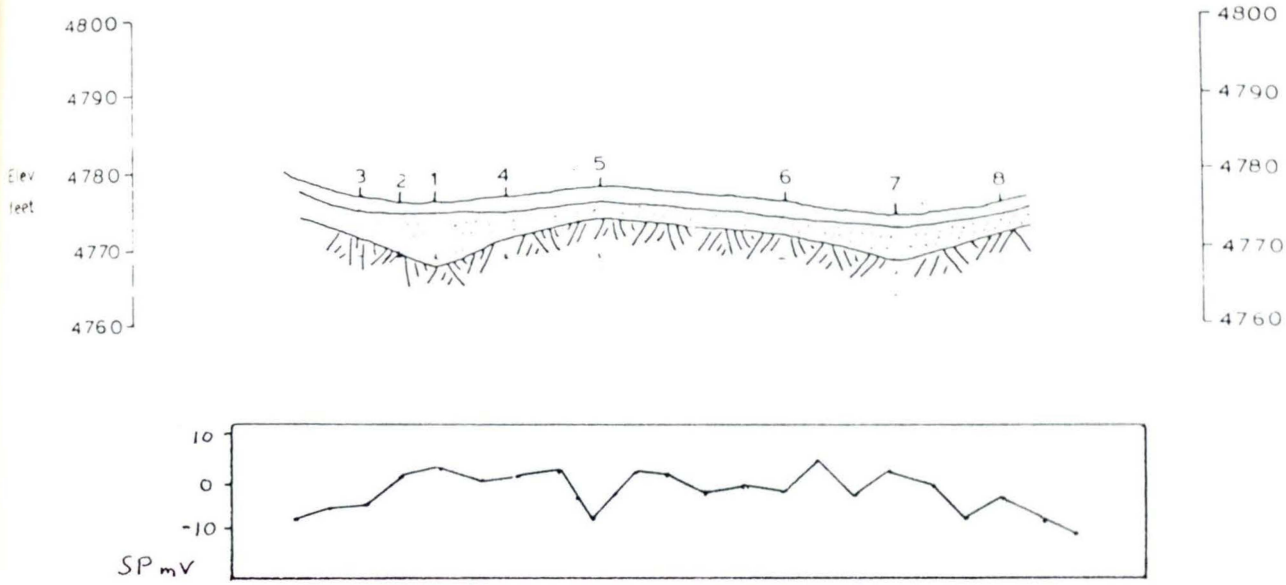


Figure 59. Self potential results at the Lean-To Ridge site.

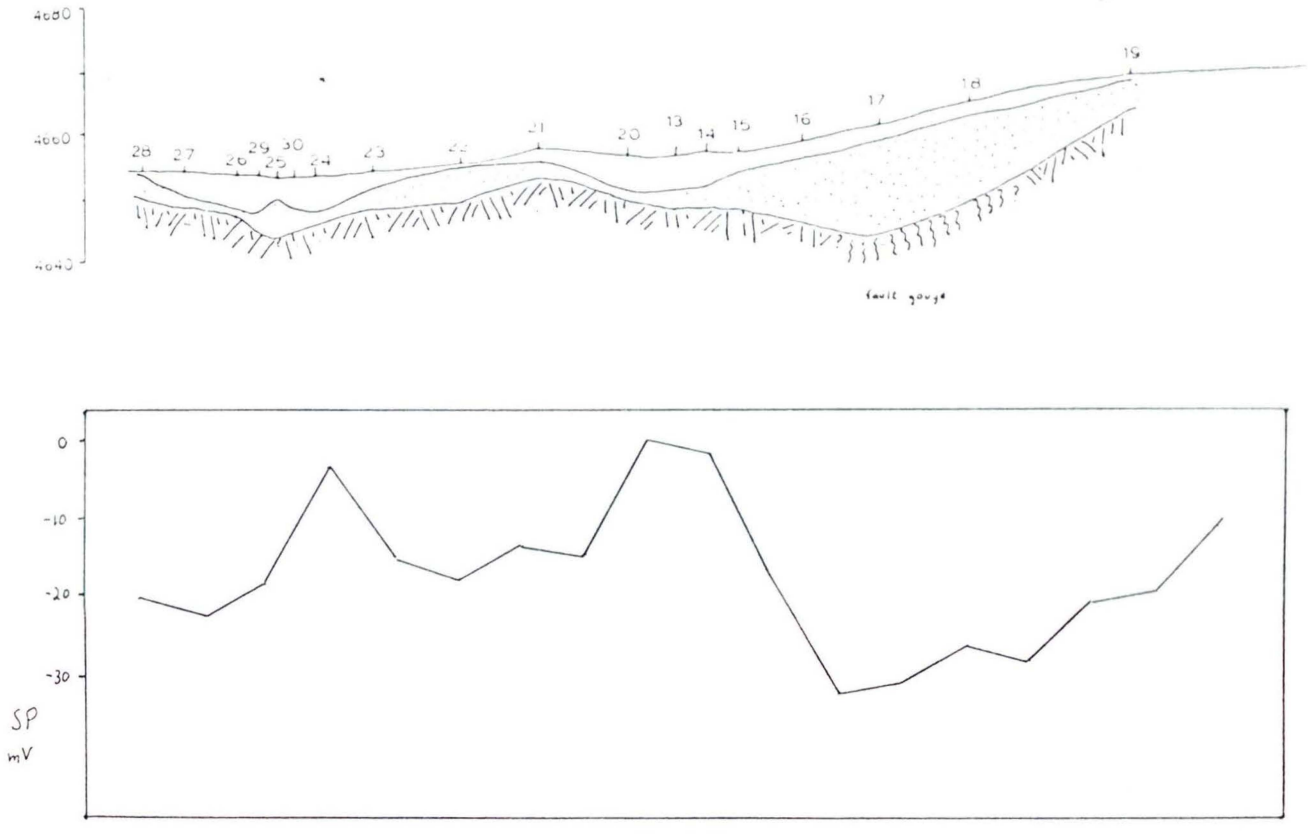


Figure 60. Self potential results at the Dan Lee Ridge site.

BASIC PRINCIPLES

Electromagnetic induction methods (EM) measure the bulk electric conductivity of the subsurface. EM measurements are similar to those made by conventional resistivity surveys but EM techniques are much faster because the measurement is made without ground contact. However, EM methods do not work well in high resistivity environments. Several commercially available systems are especially configured for shallow engineering investigations.

Terrain conductivity can be measured directly by electromagnetic induction. Instruments used for this purpose include the Geonics EM31, EM34-3, and EM38. The coils on the EM31 and EM38 are separated by fixed distances of 3.67 m and 1 m, respectively. These coils may be oriented in the horizontal dipole or vertical dipole modes. The coils of the EM34-3 may be separated by a distance of 10 m, 20 m, or 40 m. Usually, the coils are oriented in the horizontal dipole mode. In the appendix, a BASIC program (EM12) useful for interpreting terrain conductivity measurements is described.

The program can calculate the following:

1. The cumulative response function (CRF), for the vertical or horizontal dipole modes. The user must enter the coil separation and the depth.

2. The apparent conductivity of an n-layered system. The user must enter the coil separation, the thickness of each layer, the conductivity of each layer, and the conductivity of the underlying halfspace.
3. Conductivity solution of a one-layer over a halfspace system. For the EM31 and EM38 units, two independent apparent conductivity measurements are made using the vertical and horizontal dipole modes. For the EM34-3 unit, two independent apparent resistivity measurements are made at separations s and 2s. The user must enter the coil separation, assumed thickness, and the two independent apparent resistivity measurements.
4. Thickness of a one-layer over a halfspace system. The user must enter the coil separation, the conductivity of the layer, the conductivity of the halfspace, and either the horizontal or vertical dipole apparent resistivity measurement.

Another BASIC program (EM9) computes the apparent conductivity of a system of horizontal layers over a halfspace for a horizontal loop electromagnetic induction system. Any number of layers can be modelled. The ratio of loop separation to skin depth must be much less than unity for the method to be valid.

The formulas used are shown in the appendix. More information can be found in McNeill (Electromagnetic terrain conductivity measurement at low induction numbers, Technical Note 6, 1980, Geonics Ltd., Mississauga, Ontario). The constant K in the formulas calibrates the measurement so that it is correct over the earth's surface at a given height. This calibration assumes that all measurements are made at this same height.

The highly resistive soils and groundwater in central Idaho are not at all conducive for using the EM method to find either the bedrock surface nor the water table. Using a Geonics EM-31 instrument, we failed to get a significant response at Sites 1 or 3. The high resistivity of bedrock, the soil cover, and the ground water make this technique useless in the gruss-covered terrain of central Idaho.

BASIC PRINCIPLES

Geophysical methods are typically used by engineers to investigate the subsurface where drilling is too costly or time consuming. Ground penetrating radar (GPR) is an appealing alternative to conventional seismic refraction and electrical resistivity because it yields continuous subsurface profiles which can be displayed at the site for immediate interpretation. Data collection is far faster than other methods over smooth open terrain.

GPR systems have been under development for the last several decades. These systems have been used by engineers to determine the thickness of ice and snow (Campbell and Orange, 1974); to evaluate peat and coal resources (Ulriksen (1982); to delineate features in tunnels and mines (Rubin and Fowler, 1978); Stewart and Unterberger, 1976; Coon, Fowler, and Schafers, 1981); to locate buried fault scarps (Bilham, 1985); to locate subsurface cavities (Fountain, Herzig, and Owen, 1975); to profile lake and river bottoms (Morey, 1974); and to locate buried utility lines and cables (Morey and Herrington, 1972).

More germane to this study is the use of GPR in profiling mineral soils (Benson and Glaccum, 1979), organic soils (Ulriksen, 1982), and histosols (Doolittle, 1983); in characterizing soil units (Doolittle, 1982); and in estimating moisture content as a function of depth (Houck, 1984).

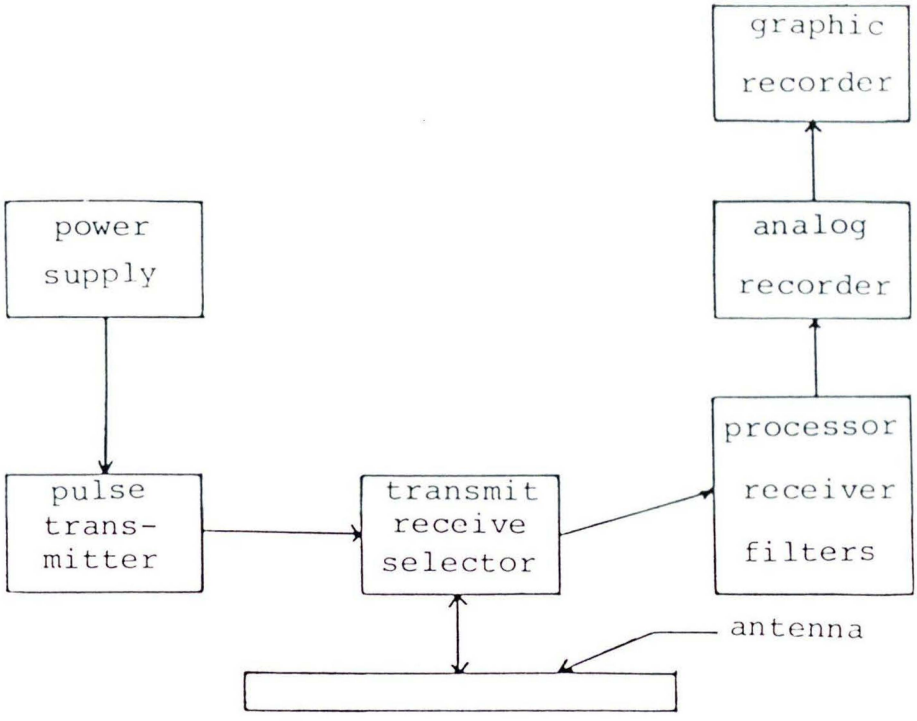


Figure 61. GPR system components.

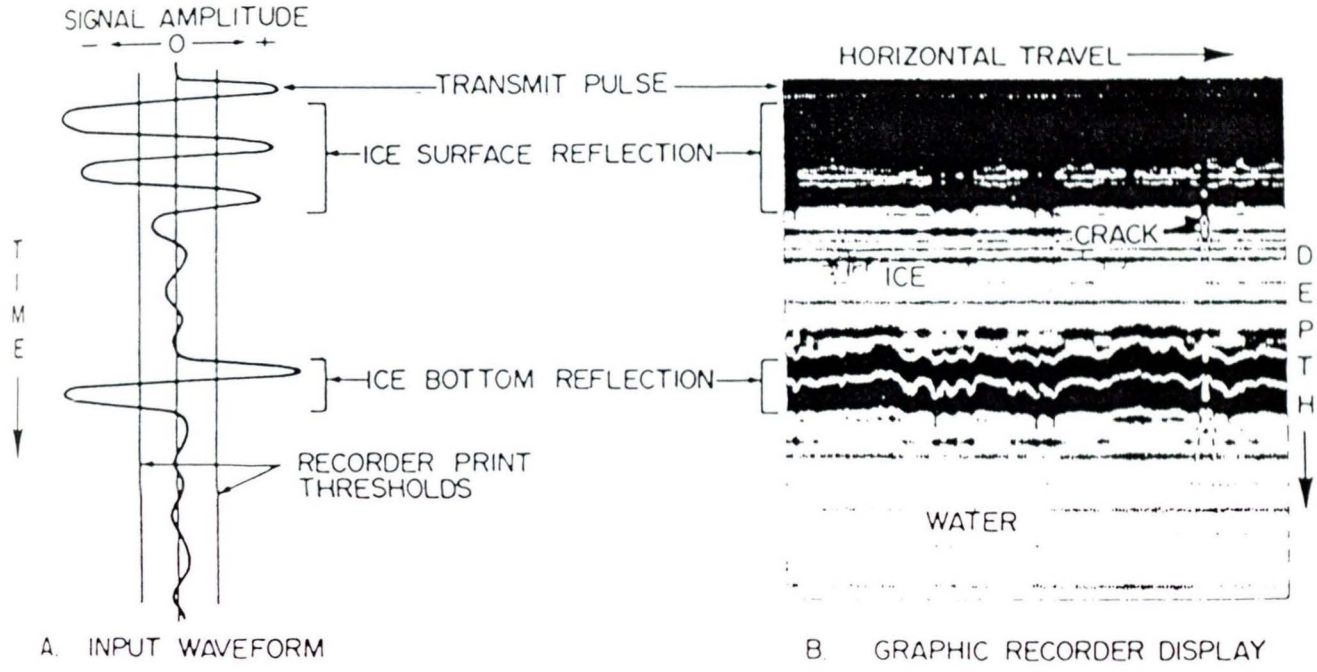


Figure 62. GPR data presentation.

Typical GPR units consist of seven components: power supply, transmitter, transmit antenna, receive antenna, signal processor, data recorder, and printer (Figure 61). The transmitter and transmit antenna emit an electromagnetic pulse at radar frequencies which propagate into the ground. Portions of this energy are reflected back due to changes in the electrical properties of the soil and rock. The reflected signal is detected by the receive antenna, processed, and recorded, and displayed (figure 62). Antennas designed for frequencies in the range of 50 to 500 MHz have proven to be effective for use in most earth materials.

Continuous GPR surveys are performed by moving the transmit and receive antennas together along the surface with a fixed separation of zero to ten feet as illustrated in Figure 63. The signals received are displayed as a plot of traverse distance versus two-way travel time in a manner analogous to seismic reflection sections. To convert two-way travel times to depth, the effective radar propagation velocity of the material above the reflecting layer must be known.

At sites showing dipping layers, the records obtained by continuous profiling are like unmigrated seismic reflection records: the reflecting points on the dipping beds do not appear in their correct subsurface positions, but are displaced laterally and downward from their true positions. The process of transforming apparent reflecting position to true positions is called migration. This process, like the conversion of arrival times to depth, requires knowledge of the radar propagation velocities in the subsurface.

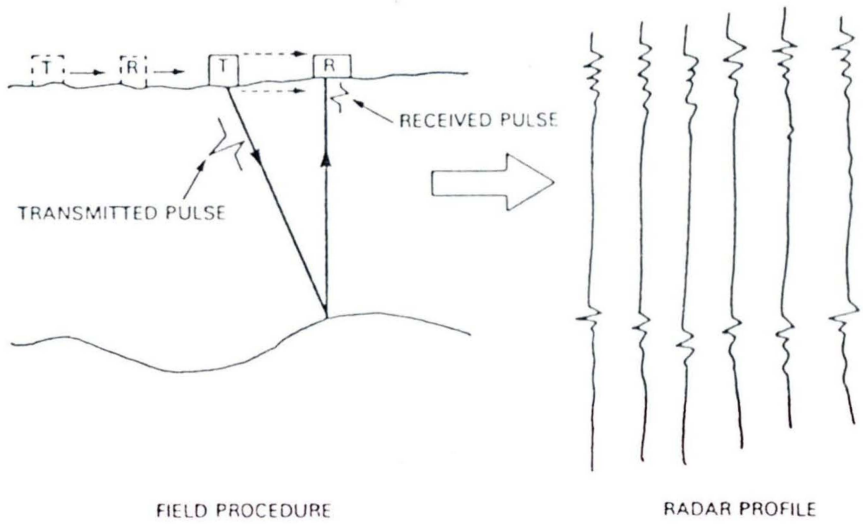


Figure 63. A continuous GPR survey setup. After Houck, 1984.

Radar velocity can be determined from the GPR field procedure called a velocity survey, which involves measurements at increasing antenna separation as illustrated in Figure 64. On the resulting data plot--a velocity profile--the direct arrivals which travel horizontally through the air and ground, exhibit linear moveout with a slope equal to the inverse of the respective velocities. The reflected arrivals exhibit hyperbolic moveout in a manner similar to seismic reflections. The velocity of the material above the reflective layer is computed with the X^2-T^2 method for which the travel times (T) at corresponding antenna separations (X) are picked off the radar record, squared, and plotted. The slope of the line is equal to the inverse of the velocity squared.

Radar reflections occur at discontinuities in relative permittivity. Relative permittivity--also known as the dielectric constant-- is the ability of a material to store charge when subjected to an electric field Table 4). In a dielectric medium, the relative permittivity can be related to velocity propagation by:

$$er = SQRT(c2/v2)$$

where er is the relative permittivity, c is the speed of light in free space, and v is the radar propagation velocity.

The relative permittivity of water is higher at radar frequencies than the relative permittivity of soil or rock. Therefore, changes in water content caused by fracture systems, changes in degree of saturation at the water table, and changes in porosity in the saturated zone can result in radar reflections. Davis and his co-workers (1977)

quantified the dependence of relative permittivity on volumetric water content. This relationship can be used to estimate soil volumetric moisture content (degree of saturation times porosity) by determining radar velocities using the velocity profiling technique described above. Relative permittivity and then moisture content are computed from the two equations above. Houch (1984) expanded this method for the case of a multi-layered earth model.

Radar reflections also result from large changes in relative permittivity associated with subsurface cavities, clay layers, and buried metallic objects.

The depth to which radar penetrates the earth is controlled primarily by conductive attenuation-- as conductivity increases, the depth of penetration decreases. Loss of energy due to scattering also limits penetration in inhomogeneous material. The conductivity of soil generally depends on water content, the conductivity of the contained water, and the clay content. Therefore, radar penetrates a few tens of feet in clean soils with low water content or fresh water content, but less than 2-3 feet in clayey soils or in soils containing highly conductive water.

Conductivity of soil also increases with increasing frequency of the radar pulse. Therefore, the depth of penetration can be increased by transmitting a lower frequency pulse. Hoover, resolution is sacrificed by this procedure because the wavelength is longer.. Also, lower frequency antennas are larger and more awkward to handle in the field.

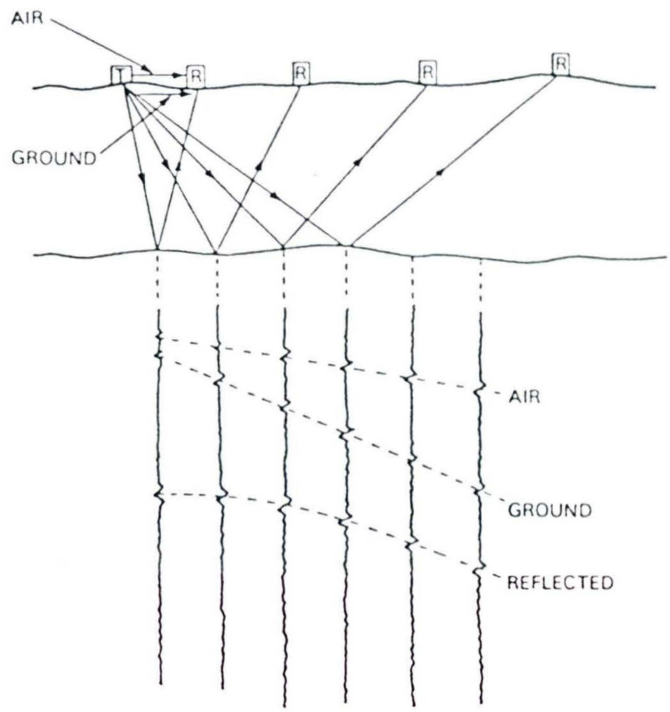


Figure 64. A GPR velocity survey setup.

Material	Approximate Conductivity (mho/m)	Approximate Dielectric Constant
Air	0	1
Fresh Water	10^{-4} to $3*10^{-2}$	81
Sea Water	4	81
Sand "Dry"	10^{-7} to 10^{-3}	4 to 6
Sand, "Saturated"	10^{-4} to 10^{-2}	30
Silt, "Saturated"	10^{-3} to 10^{-2}	10
Clay, "Saturated"	10^{-1} to 1	8 to 12
Marshy Forest Land	$8*10^{-3}$	12
Rich Agricultural Land	10^{-2}	15
Fresh Water Ice	10^{-4} to 10^{-2}	4
Granite "Dry"	10^{-8}	5
Limestone "Dry"	10^{-9}	7

Table 4. Approximate VHF Electromagnetic Parameters

Material	Attenuation in Decibels/Meter Frequency in MHz 1	10	100	500
Pure Water	0.025	0.039	0.408	16.191
Sandy Soil (moist)	0.471	0.513	0.773	4.407
Clay Soil (dry)	0.013	0.075	0.425	1.649
Clay Soil (moist)	0.780	3.803	17.93	53.75
Sea Water	34.50	108.54	326.54	592.03
Granite	0.732×10^{-5}	$.732 \times 10^{-5}$	$.732 \times 10^{-5}$	$.732 \times 10^{-5}$

Table 5. Radar attenuation in various earth materials.

TEST SITE RESULTS

GPR continuous subsurface profiles and velocity profiles were performed at four sites during the fall seasons of 1984 and 1985. Radar equipment used was the XADAR System IV and the OYO YL-R2 GEORADAR System.

Site 1 and 3

Figure 65 shows velocity surveys recorded at Site 1, Dan Lee Ridge using both OYO and GSSI equipment. The strong linear second arrival is the direct ground wave with a velocity of 0.28 ft/ns. This velocity corresponds to a relative permittivity of 14, a value typical of damp soil. Reflections arrive after the direct wave and show hyperbolic moveout. The shallower reflections show stronger amplitude at close transmit-receive antenna separations of 10 to 20 feet. This effect is due to the strong dependence of electromagnetic reflection coefficients on the angle of incidence and indicate that the antenna should be separated to record the deeper ground water surface which was measured 12 feet below the ground surface the previous month.

The velocity surveys certainly show air wave and ground wave arrivals. However, how reflectors are to be picked out from noise appears to be somewhat of a mystery. In fact, all the events (other than the ground wave) appear to moveout in a manner suspiciously similar to the air wave or the ground wave, particularly between 10 and 30 feet.

Many of the presumed reflectors may simply be repetitious air wave arrivals due to ringing in the antennas.

Figure 66 shows a continuous profile of this site using the GSSI equipment using an antenna separation of 10 feet. The velocity profile (Figure 65) shows that at an antenna separation of 10 feet, the air wave arrives at about 15 ns, and the ground wave at about 60 ns. Air and ground wave arrivals can clearly be seen near these times on Figure 66. Care must be taken not to interpret these events as reflections from a horizontal feature. Variations in the arrival time of the ground wave on the profile probably signifies variations in moisture content in the soil surface.

Because the first continuous span appeared noisy, a second profile was run in 1985 using OYO's equipment (Figure 67). The OYO unit allows recording a single wiggle trace while the antenna are stationary, then moving ahead a short distance, and recording another. The final product is a nearly continuous profile. Figure 67, like the previous year's record, shows much scatter, but only to depths of about 13 ft (100 ns). The reflected surface apparent in Figure 66 is not evident, possibly because no antenna separation was used in the later study.

Figure 68 shows a velocity profile from Site 3, Lean-To Ridge. The direct wave shows a velocity of about 0.33 ft/ns, which corresponds to a relative permittivity of 9 indicating that the soil here has less moisture than the soil at Site 1, as would be expected on a south aspect in the fall. Figure 69 shows the subsurface profile at Site 3, and the corresponding radar profile. The apparent change in character of the

radar section between boreholes 5 and 6 is due to a change in instrument settings. The thickness of the ash cap and colluvium, is fairly consistent at about 4 to 6 feet, thickening to 8 feet in drill hole 1. The radar profile (Figure 69) shows a gentle undulating surface at a depth of about 7 feet; somewhat deeper than the colluvial-residual soil contact. The groundwater level at this site was fairly level at about 8.5 to 10 feet below the surface during the fall season. Because the thicker soil under drill hole 1 is not indicated in the radar profile, the reflection might correspond to the water table, not the base of the colluvium. Unfortunately, the velocity profile did not show a deeper reflector to enable the calculation of a velocity change that might confirm an increase in saturation due to the water table. Reflections are apparent on the velocity profile from depths of about 15 feet corresponding closely to the bedrock depth observed in drill hole 9.

Below drill holes 1 and 9 reflected energy occurs below 100 ns. No holes were drilled deep enough to investigate its source. The coherent event at about 125 ns across the entire record is instrument noise.

Figures 70 and 71 show subsurface profiles on the Lean-To Ridge Road above Site 3. Both of the radar profiles show dipping apparent reflectors. The parallel lines in Figure 71 are probably multiples of the same phenomenon. Both the OYO and XADAR profiles show a bed dipping at about 35 degrees, but only the XADAR profile shows the shallower bed dipping at about 16 degrees. There is no readily apparent fracture zone, foliation, or lithology change in the drill core to explain the dipping events in the radar profiles.

The foliation and schistocity in the gneiss varies in dip from 20 to 55 degrees. A one foot thick granodiorite dike is the only unit that is easily traced from drill holes 1 to 4. It is younger than the gneiss and has an apparent dip of about 20 degrees. The gneiss immediately above and below the dike is different from hole to hole. While the biotite content (and percentage of schist) is higher in drill holes 1 to 4, the dips vary widely and there is not a distinct traceable unit to explain the strong reflectors.

The more gently dipping event on the XADAR record appears to have a lower frequency content than normal. Perhaps this event is a trapped mode, similar to seismic ground roll. Because of its lower frequency content, it may have been eliminated on the OYO record by the frequency filter. The other event which appeared on both records may be a diffraction pattern. At any rate, these radar records indicate that what appear to be spectacular reflections may not have any geological significance that could be identified in the drill core.

Site 4 Kessler Creek

The third site tested was 7 miles northwest of Riggins, Idaho in the Nez Perce National Forest in carbonate terrain. Surface depressions along a proposed road location suggested the possibility of caverns. This site was not drilled, but seismic refraction surveys were performed.

The radar velocity profile in Figure 72 shows a direct wave with a velocity of 0.25 ft/ns corresponding to a soil with relative permittivity of about 16. The deepest discernable reflector on the velocity profile yielded an average velocity of 0.34 ft/ns and a relative permittivity of 9. The increase in radar velocity with depth may be due to a decrease in the moisture content. The depth to the deepest reflector on the velocity profile was calculated to be 13 ft--a value verified by a seismic refraction survey.

Because this site was not drilled, we could not verify our interpretations of the radar profiles run at this site. Although some correlation was found between bedrock depressions located with a seismic refraction survey and radar anomalies, we found no coherent radar reflector that we could correlate with either the bedrock surface or the water table.

Site 5 Grouse Creek Landslide

The fourth site tested was located 11 miles southeast of Grangeville, Idaho in the Nez Perce National Forest. The geology consists of approximately 20 ft of clay-rich decomposed basalt overlying micaceous gneiss. A translational landslide exists in the basalt soil. The velocity profile in Figure 73 is starkly different from the previous sites. The only discernable arrivals are associated with the direct air

wave. The clay soil at this site has sufficiently high electrical conductivity that even the direct ground wave was attenuated before reaching the receive antenna. Here, GPR is clearly an inappropriate tool.

It is curious that the velocity survey (Figure 73) shows events to 80 ns despite the fact that reflectors and ground waves are impossible at this clay-rich site. These reverberating air wave arrivals are probably present on all the radar records at all the sites studied. Their presence certainly must obscure interpretation of ground penetrating radar data.

DISCUSSION

The ground penetrating radar method has severe limitations as a routine technique for shallow site investigation. These shortcomings pertain to ground penetration, instrumentation, field technique, data processing, and interpretation. The effective depth of penetration of GPR is limited by the conductivity of the soil. In clay soils, the penetration depth may only be a few inches, rendering the technique useless for subsurface investigation. In heterogeneous soils, scattering of the radar waves from shallow features can obscure more important deeper reflections. Attempts to increase penetration depth by using lower frequency pulses result in lack of resolution of shallow subsurface layers.

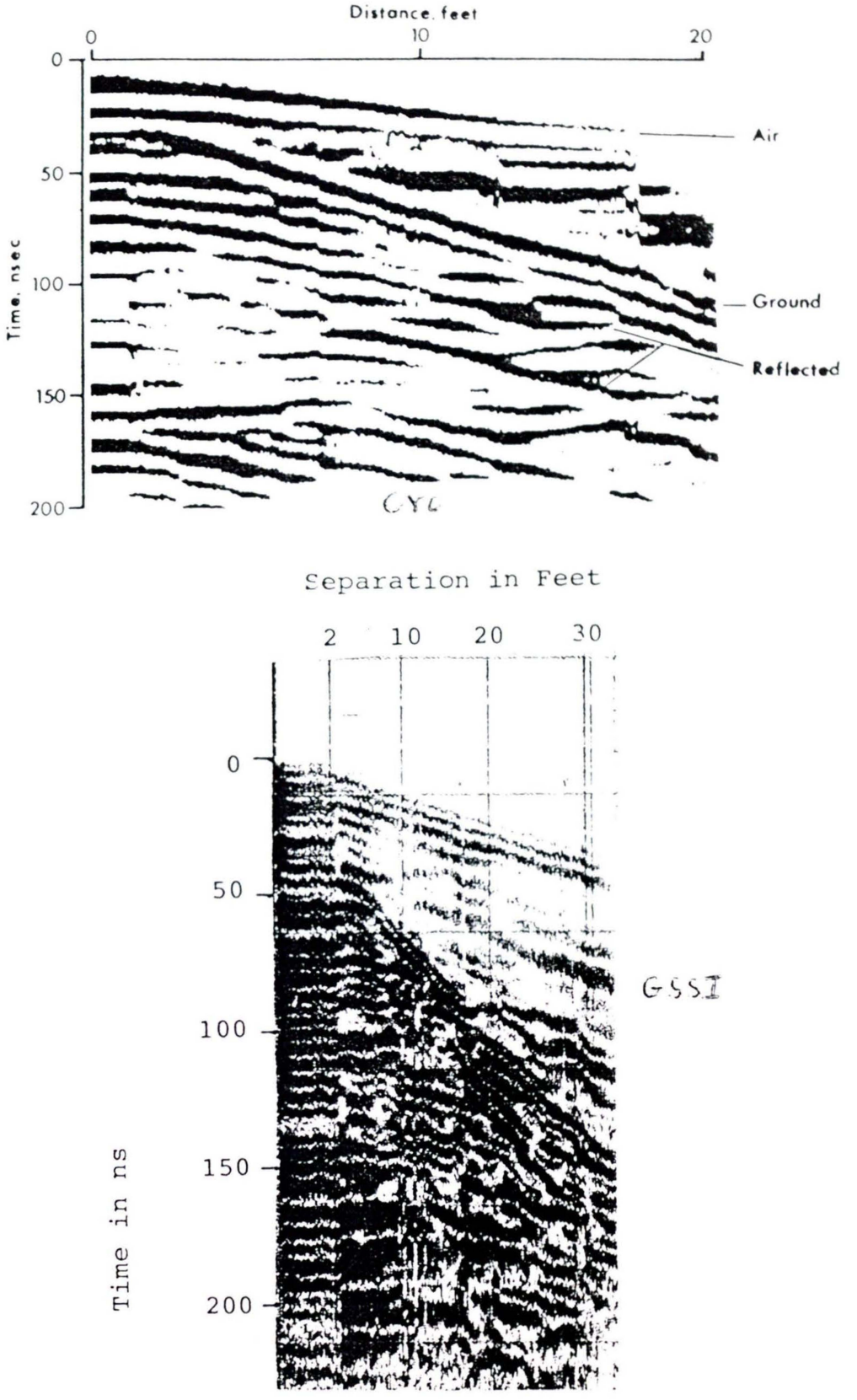


Figure 65. GPR velocity surveys at Site 1, Dan Lee Ridge.

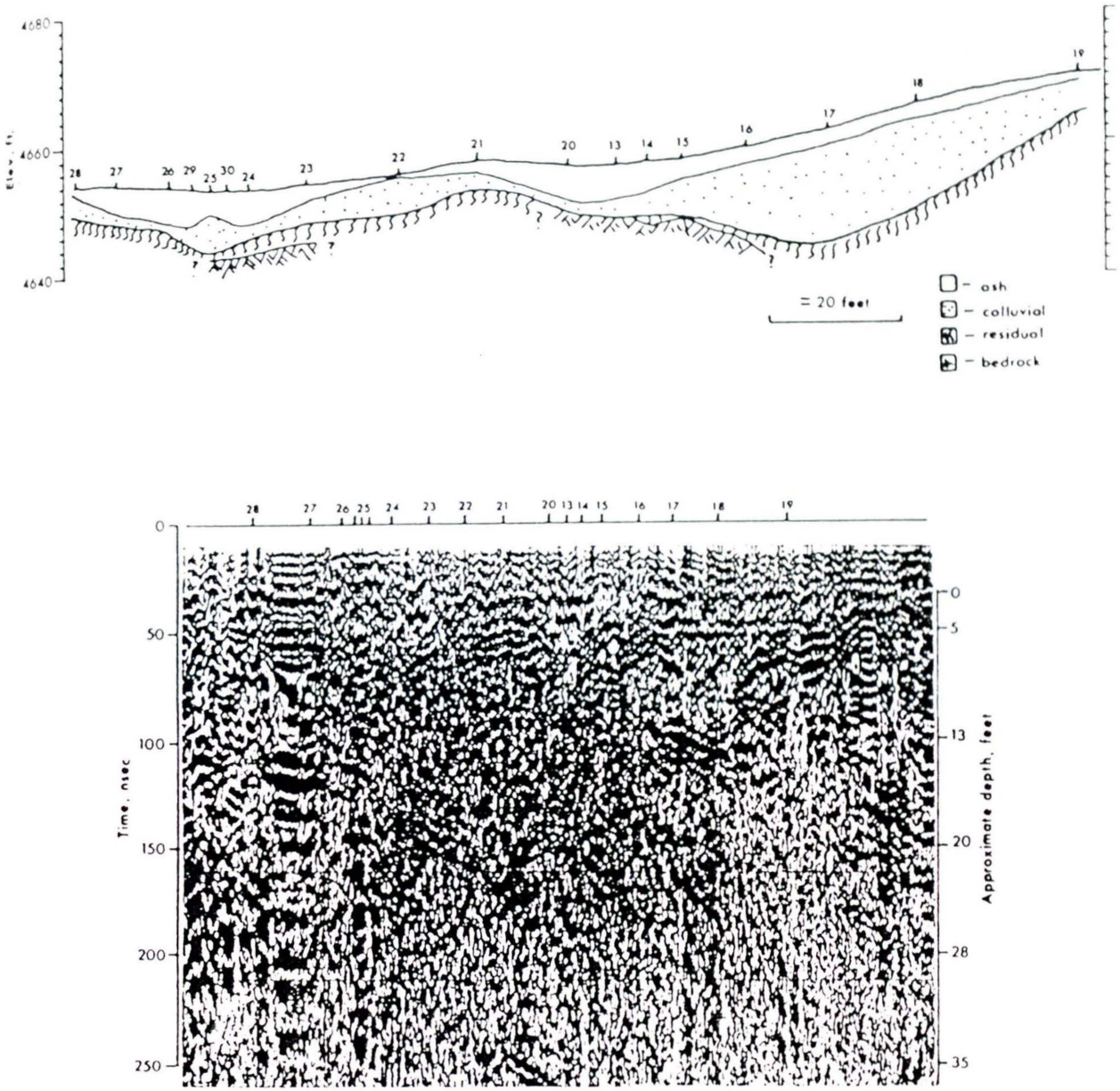


Figure 66. Continuous GPR survey at Site 1 using the GSSI equipment.

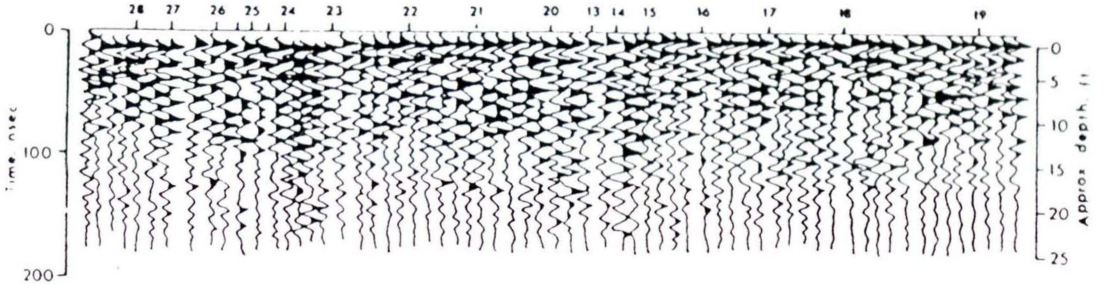


Figure 67. Continuous GPR survey at Site 1 using the OYO equipment.

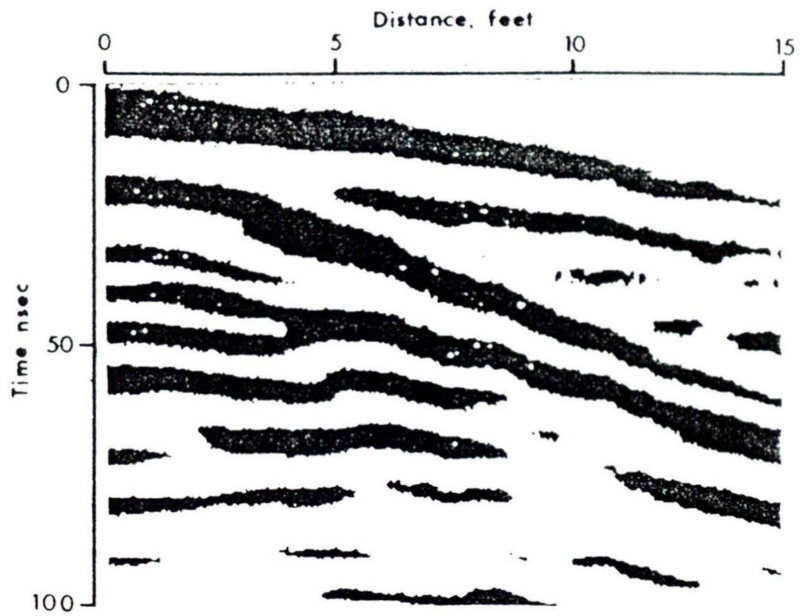


Figure 68. GPR velocity survey at Site 3, Lean-To Ridge.

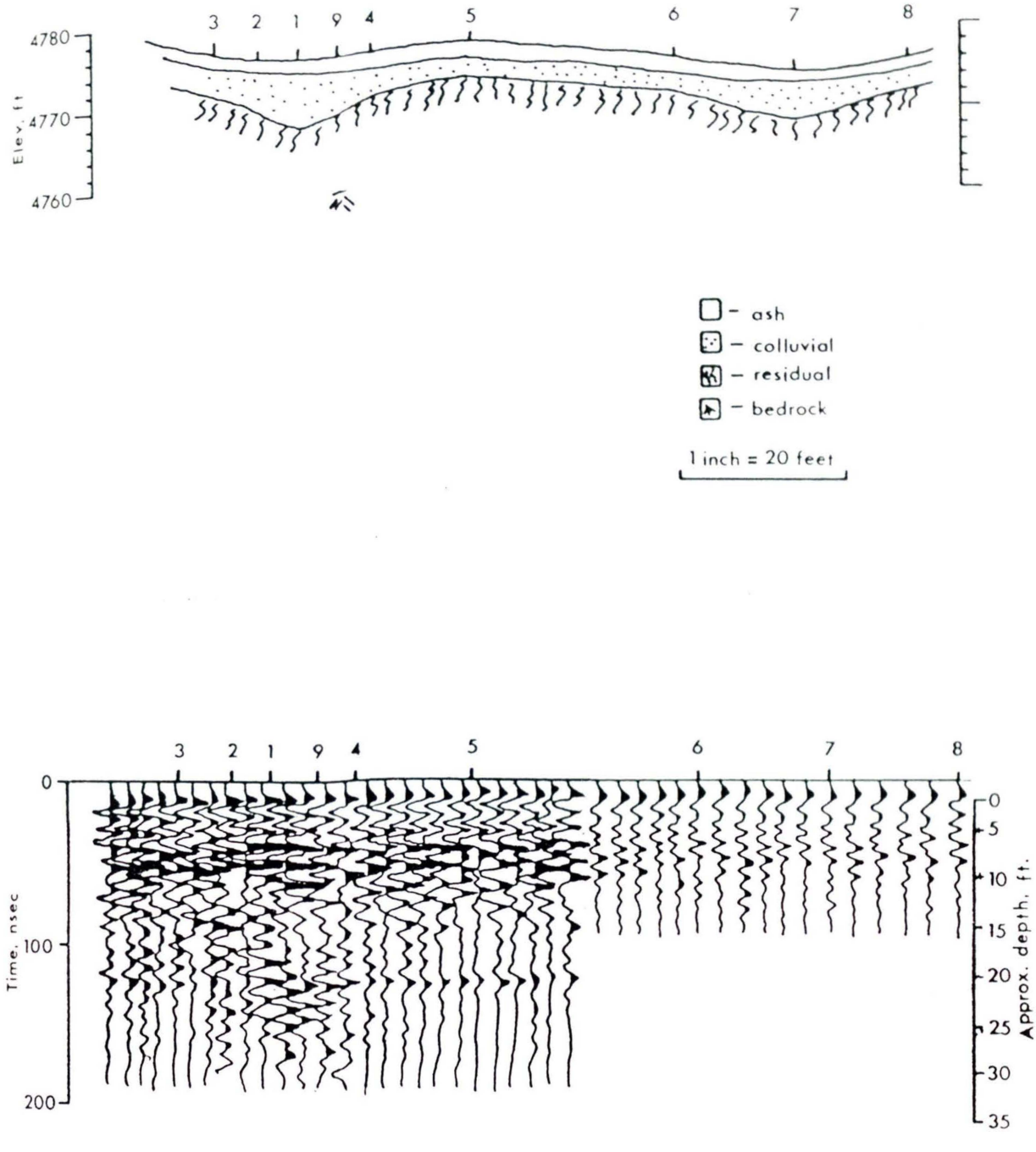


Figure 69. GPR profile at Site 3, Lean-To Ridge.

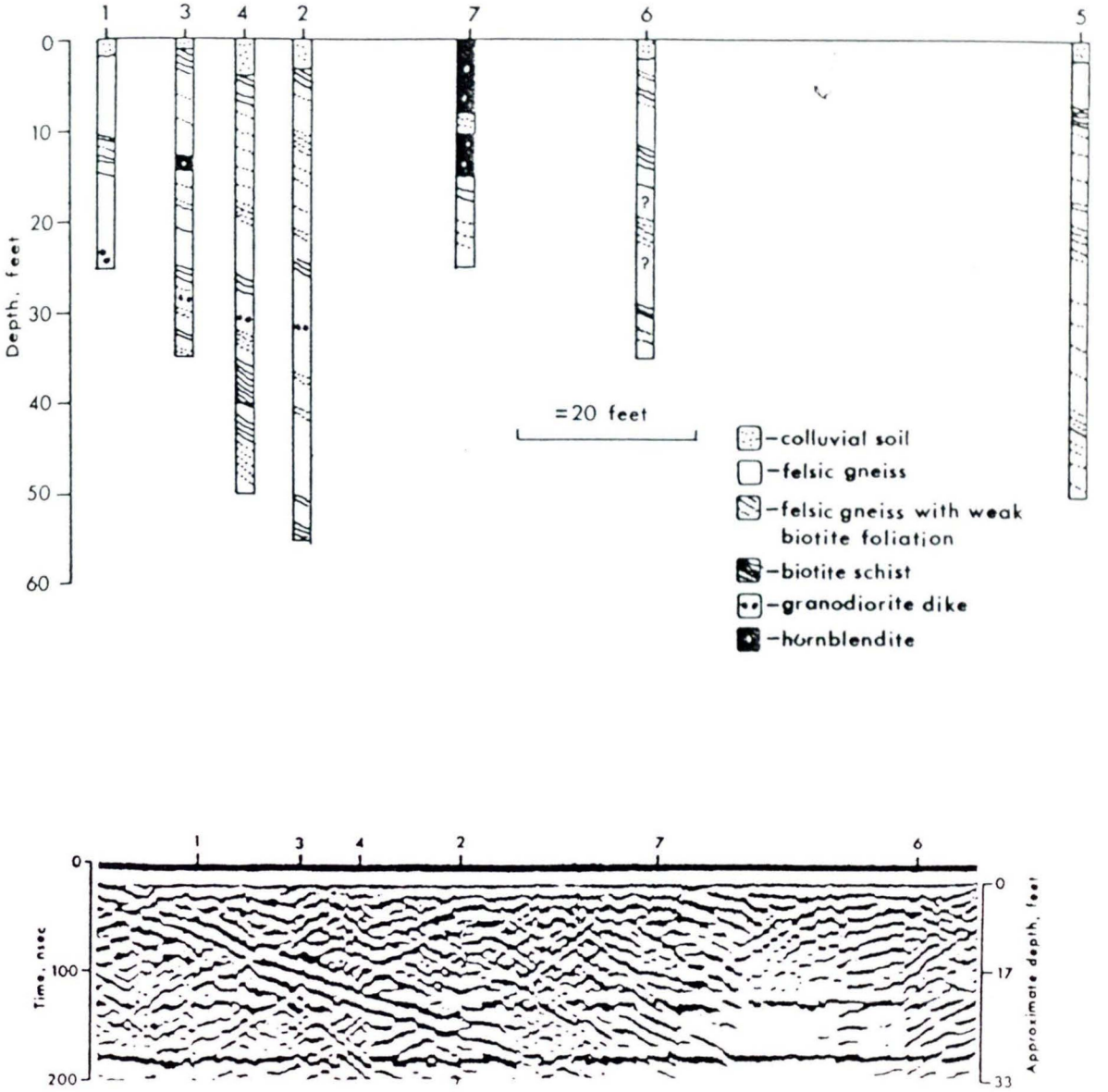
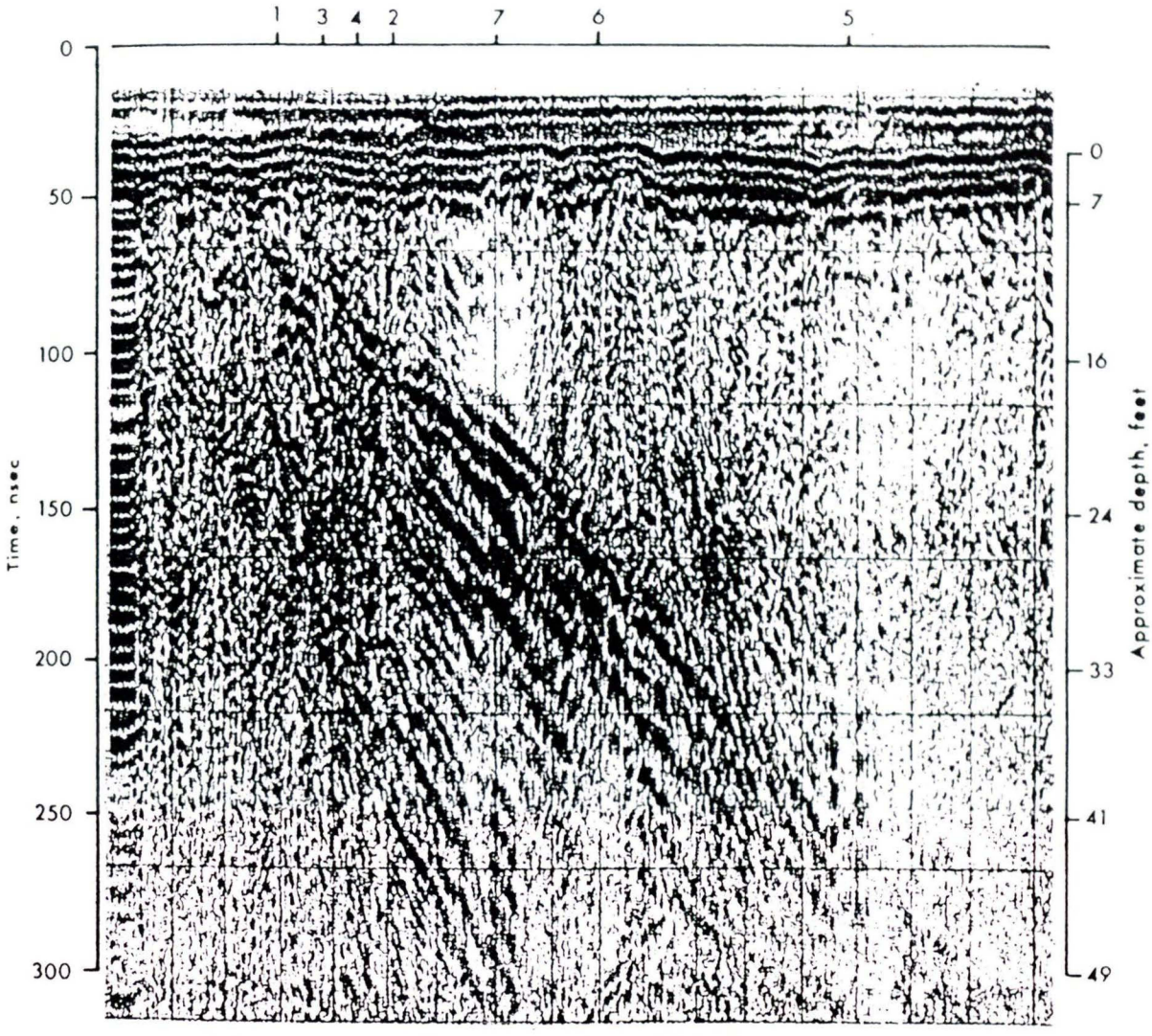


Figure 70. Subsurface profile and GPR surveys on road above Site 3, Lean-To ridge.



Continuous profile showing dipping apparent reflectors using the XADAR system.

Figure 71. Continuous profile on the Site 3 Road.

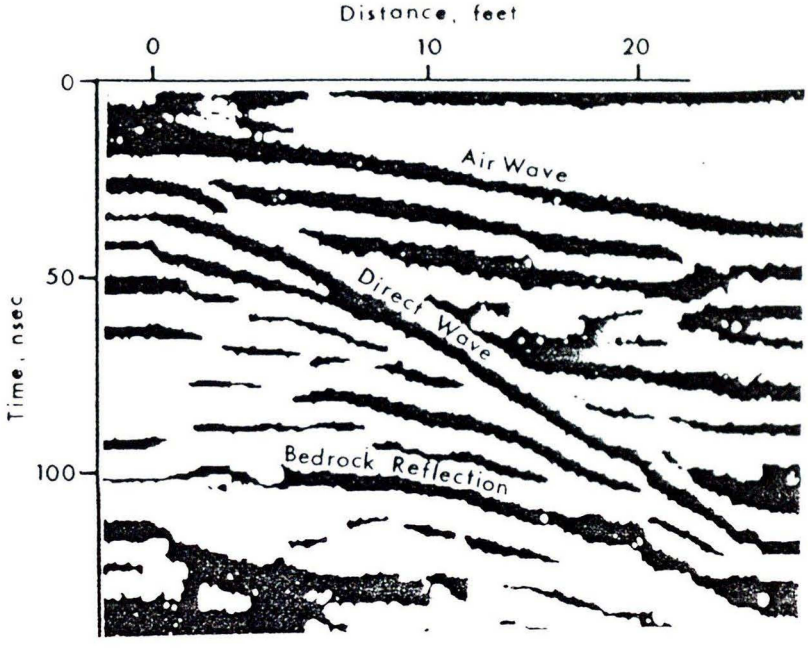


Figure 72. GPR velocity survey at Site 4 in carbonate terrain on the Nezperce National Forest.

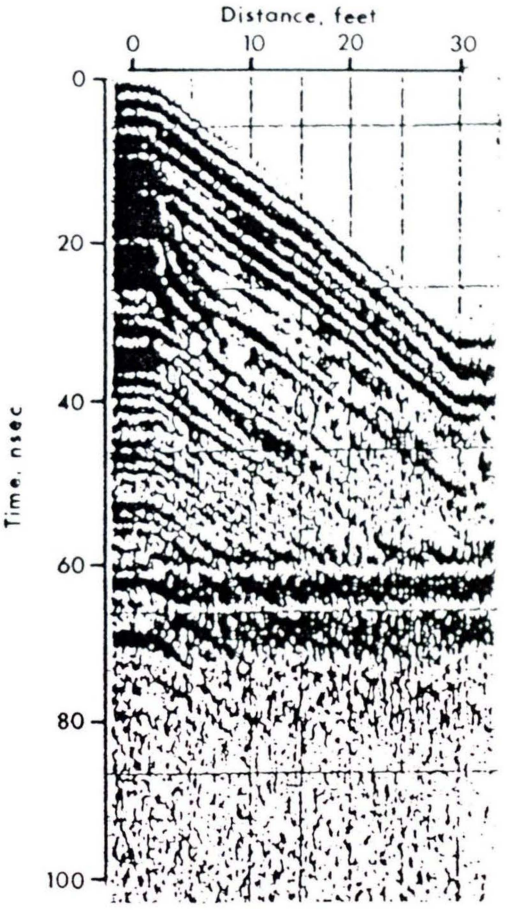


Figure 73. GPR velocity survey at Site 5 on the Grouse Creek Landslide in basaltic terrain southeast of Grangeville, Idaho, on the Nezperce National Forest.

Currently available GPR instrumentation is bulky and suitable only for easily accessible sites. In forested or shrub-covered areas, it is necessary to cut and smooth out a wide swath to ensure adequate coupling of the antenna with the ground.

The field technique commonly used by GPR users--continuous profiling with an occasional velocity survey--does not seem to provide sufficiently high quality data for convincing interpretation of geological and hydrological parameters. Continuous profiling with an antenna separation of more than a few feet is awkward except in very smooth terrain. On the other hand, continuous profiling without any separation between transmit and receive antennas results in poor recording of deeper reflectors. Continuous profiling does not provide sufficient subsurface velocity information for state-of-the-art data processing as used in seismic reflection work. The coherent quality of the velocity profiles obtained in this study indicate that reflections are occurring, but the incoherence of the continuous profiles suggests that the reflections are not being efficiently recorded. There is a clear need for common-depth-point field techniques--the standard approach in modern exploration seismology--to be applied to GPR surveys. However, the logistics of such a field technique may be neither practical nor economical for routine engineering site investigation. The prevalence of diffraction patterns and steeply dipping reflectors on the radar sections indicates that the sections should be routinely migrated for proper interpretation but the present field techniques and instrumentation are insufficient for such sophisticated methods. It is

not surprising, therefore, that GPR radar sections are difficult to interpret even at the relatively simple sites considered in this study.

On the positive side, the velocity profiles obtained in this study indicate that radar is capable of penetrating to several tens of feet in much of the forested areas of northern Idaho. The commercial equipment functions well; it is rugged, water resistant, and electronically sophisticated. At present, GPR may not be a routine tool for geotechnical site investigation, but the technique has promise for geotechnical research.

EVALUATION OF A CONSULTANT'S REPORT: Ground Penetrating Radar

During the week of 24 September 1984, personnel from XADAR Corporation, the University of Idaho, and the USDA Forest Service were present to observe ground penetrating radar surveys at three sites in northern Idaho. The purpose of these surveys was to evaluate the ability of the radar to measure some of the physical properties of the near-surface layers in a mountainous terrain. Because future use of radar systems may involve the use of outside consultants, a critical review of the consultant's report (Fowler, 1984) is given here.

The first test commented on was the GSSI velocity survey along a survey line at Site 1 (Figure 64). The consultant's interpretation was as follows:

> This survey shows a well-defined ground wave and several possible reflections coming in below the ground wave. The ground wave velocity is about .270 ft/ns which corresponds to a dielectric constant of 13.8. This is very reasonable for a damp soil. The reflection near 150 ns can also be located at 20' separation near 162 ns. This would correspond to an average velocity of .28 ft/ns and a depth of 21 feet for the reflector. Other reflections are visible in the data, however, it is difficult to trace them across the section. This section shows that radar can penetrate the soil layer in this area and that reflections can be seen.

This velocity survey certainly does show air wave and ground wave arrivals. However, how the reflector at 162 ns was picked out from what appears to be a series of events is somewhat of a mystery. In fact, all the events (other than the ground wave) appear to moveout in a manner suspiciously similar to the air wave, particularly between 10 and 30 feet. Could all the presumed reflectors actually be repetitious air wave arrivals due to ringing in the antennas? The consultant's argument that the events arriving after the ground wave are reflections is not all that convincing.

The next comment was on the reflection profile at Site 1 (Figure 66). For this line, a constant separation of 10 ft was maintained between the transmitting and receiver antennas. The consultant's interpretation was as follows:

> Several different things can be seen in this profile. The first thing is that the character of the profile is different in the middle section than from the ends. The middle section has many strong reflectors while the end portions have much less reflection energy. The numerous incoherent reflectors in the center section is usually indicative that the soil contains large rocks or other scatterers.

This statement is somewhat incredulous. A glance at the distances shows that the antenna were not dragged at a constant speed across the surface. In fact, the antenna commonly got stuck on brush and stumps. The "strong reflectors" are nothing more than the result of the antenna sitting in one position and repetitively sending the same signal.

Obviously, in the antenna cannot be dragged at a constant rate, some type of correction needs to be made to avoid interpretational errors.

The consultant's report continues:

> Two major reflectors can be seen on the profile. The first reflector occurs at about 50 ns or a depth of about seven feet. This reflection is a little over seven feet deep between the 30 and 50 foot position, then it becomes shallower around the 60 foot position.

This interpretation is absolutely astounding. At an antenna separation of 10 ft, the velocity profile (Figure 66) clearly showed no received energy other than the air wave until at least 60 ns when the direct ground wave arrived. The consultant's "reflection" is nothing more than the direct ground wave arrival. It varies across the section because the electrical permittivity varies with moisture content in the soil. The late arrivals in the vicinity of 30' and 95' correspond to topographic lows with moister soils and a slower ground wave velocity. The consultant continues:

> The second reflection occurs at the 150 ns level. This represents an approximate depth of 20 feet. The reflection remains relatively constant across the section.

How the 150 ns event was picked from other equally apparent events is a mystery. The section is, in fact, very incoherent. A few strong reflections do occur here and there but they are certainly not coherent across the profile.

Figure 74 shows the same profile as Figure 66, but this time using a higher frequency antenna (350 MHz) and a shorter time range. The consultant's interpretation is as follows

> This gives a better picture of the shallow reflectors. In this figure, it is much easier to see the shallow reflection and to follow a second reflector at about 100 ns. It is also possible to see that the higher frequency energy has more scattering than the lower frequencies and that the attenuation is greater since it is not possible to see much energy coming from the deeper portions of the section.

As for the low frequency section, the shallow "reflector" is not a reflector at all. It is simply the ground wave arrival. In fact, it looks more like a first arrival on the higher frequency data. The two areas of delayed ground wave correspond with topographic lows. The event near 100 ns may be real but there are many other similar events on the section. How is one to choose the ones that are geologically meaningful? Although, in theory, scattering should be greater on the high frequency section, this is not apparent in comparing Figures 74 and 66. In fact, the high frequency section actually appears "cleaner" and more coherent than the low frequency data.

Figure 75 shows a second radar traverse at the Dan Lee site but along the lower row of drill holes. The high frequency (350 MHz antenna) were used. The consultant's interpretation follows:

> The shallow reflection can easily be seen between 20 ns and 40 ns. The reflections on this line are more

continuous and easier to follow than on the first line.

Once again, the shallow "reflection" referred to is nothing more than the ground wave. This line is across a small draw and the delayed ground wave corresponds to the lowest area in the draw. The deeper reflectors, if there are any, are very incoherent.

A third test commented on was conducted on the gravel road at the Dan Lee site to verify the operation of the radar unit. The profile was run across a metal culvert buried about 12 ft below the road surface (Figure 76). The transmitter and receive antennas were placed adjacent to on another. The consultant's interpretation is as follows:

> The culvert is easily seen at a depth of 40 ns in the center of the section. A second major scattering object can be seen near the surface just to the left of the culvert.

This section shows that radar waves can penetrate at least 12 feet in the road bed material at this site. Unfortunately, the road bed is different from the site geology. It is interesting that even in this perfect test case, the radar response on the left is very incoherent due to the "second major scattering object." What would this shallow object be? A cobble in the road bed? If radar is this sensitive to geological material, it may be quite useless for correlation purposes without some way to smooth or filter the effect of seemingly insignificant scatterers.

Further comments were made about the radar results at Site 3. Figure 77 shows the velocity profiles obtained at this site. The consultant's interpretation is as follows:

> The surface wave has a velocity of the order of 0.33 ft/ns. This corresponds to a dielectric constant of about 9. This would indicate that the soil here has less water in it than the first site.

The consultant's report emphasizes the ground wave arrival here because it is the only clear information apparent from the velocity profile. No distinct deeper reflectors can be seen.

Figures 78 through 81 show high and low frequency profiles over the two lines at Dan Lee Ridge. The consultant's interpretation follows:

> The profiles show a shallow layer and then several deeper layers. In general, the profiles are very similar to those obtained at the Dan Lee site.

As we have come to expect, the "shallow layer" is simply the ground wave arrival. Unfortunately, the consultant is right about the profiles being similar to the Dan Lee site. These profiles, like those at Dan Lee site, are very incoherent and impossible to interpret geologically.

Figure 82 shows a radar profile over the snow lysimeter at the Lean To Ridge site. The consultant continues:

> Note the pit outline can be seen along with the position of a large scattering object in the center of the pit.

Once again, the consultants interpretation is mysterious. What pit outline? Does he mean the delay in the ground wave? Once again, a scattering object has interfered with what should be a clear response.

The final tests with the 350 MHz antennas at the Lean-To site were conducted on a dirt road at the top of the ridge. Figures 71 and 83 show the velocity survey and the profile obtained at this site. The only interpretation given by the consultant for this line was: "The profile shows dipping beds on the north end of the line." As discussed in detail elsewhere in this report, seven drill holes drilled later at this site failed to find any geological cause for the dipping events apparent on both the velocity survey and the radar profiles at this site. This was particularly disturbing because these radar records did show coherent reflectors, yet these events proved to have no geological significance.

The final test site commented on was at Site 5 on the Grouse Creek landslide. Unlike the previous sites which were in granitic terrain, the Grouse Creek slide is in primarily basalt-derived soil. Figure 73 shows the velocity survey conducted at this final site. The consultant's interpretation is as follows:

> The only arrivals which can be seen are associated with the air wave. No ground wave or reflections are visible. Therefore the site is much more conductive than the previous sites. The soil has more clay content.

The interpreter is certainly correct about the clay content of the soil. Ground penetrating radar is clearly an inappropriate tool in this

environment. However, the velocity survey (figure 14) is nonetheless interesting. It shows many clear events to at least 80 ns. These events are certainly as evident as any of the "reflectors" picked at the other sites. Yet at this site, reflectors are impossible. The events are created 100% by the air wave. How many of the events at the previous sits are simply reverberating air wave? Obviously, if the air wave reverberations cannot be removed, ground penetrating radar records are going to be difficult to interpret in geologic terms.

Figures 84 through 86 show the radar profiles at the Grouse Creek site. The consultants interpretation is as follows:

> The velocity survey was conducted in soil similar to that of the 100 foot mark. The first major scarp feature occurs between the 180 foot position and the 200 foot position. The soil characteristics also change here. Other scarps occur at 225 feet, 280 feet, and 320 feet. Figure 86 shows that by 360 feet, the soil is more like that of the beginning of the line.

This is another incredulous interpretation. After noting that the velocity survey shows that the radar is here responding only to the air wave, the interpreter proceeds to interpret the profile as if the radar is receiving ground waves which it is not. In fact, the changes in radar response over the scarps is due to the fact that the antennas had to be physically lifted or bounced over the scarps. The changes in the profiles had nothing to do with soil characteristics but a lot to do with the ground to antenna interface. A casual observer looking at the profiles from Grouse Creek would think they are the best profiles obtained at any of the sites. In fact they are 100% noise. How much of

this noise in the profiles from the other sites? How much incoherence was placed on the profiles at the other sites by variable transmitter-to-ground coupling?

The consultant listed several conclusions that could be drawn by the quick series of radar tests that were performed. We will list his conclusions and comment on them one at a time.

1. "The radar performs very well in resistive soils. The layers can be seen and with some care and help can be mapped" This observation is dubious at best. The culvert test showed that ground penetrating radar could find a large metallic object buried 12 feet deep in a road bed. Several of the velocity surveys and profiles showed that the direct ground wave could be detected. However, none of the tests showed conclusively that reflections from geological interfaces were present. In some cases, the "reflections" picked were actually ground waves. In other cases, the events picked could not be correlated with geology and were probably instrument reverberations.
2. "The uneven surface causes some problems with the current antennas, however, by moving most of the limbs and large rocks to the side it is possible to survey." The profiles were completely incoherent probably due to the varying antenna-to-ground contact in the forested sites. It is virtually impossible to level a forest site sufficiently to obtain a sufficiently good record. The best quality profiles we obtained were on roads.
3. "More equipment development might be needed before a system could easily operate in a forest-covered area." This is certainly a true statement. The antennas are awkward and bulky, virtually impossible

to drag smoothly except on roads. The variable antenna-to-ground contact seems to create hopelessly incoherent records. Some manner has to be devise to design lightweight portable antennas that would maintain a constant relationship between readings with the ground surface in forested terrain. This might be a hopeless goal. Perhaps, airborne ground-penetrating radar is possible, but such systems do not exist at the present time.

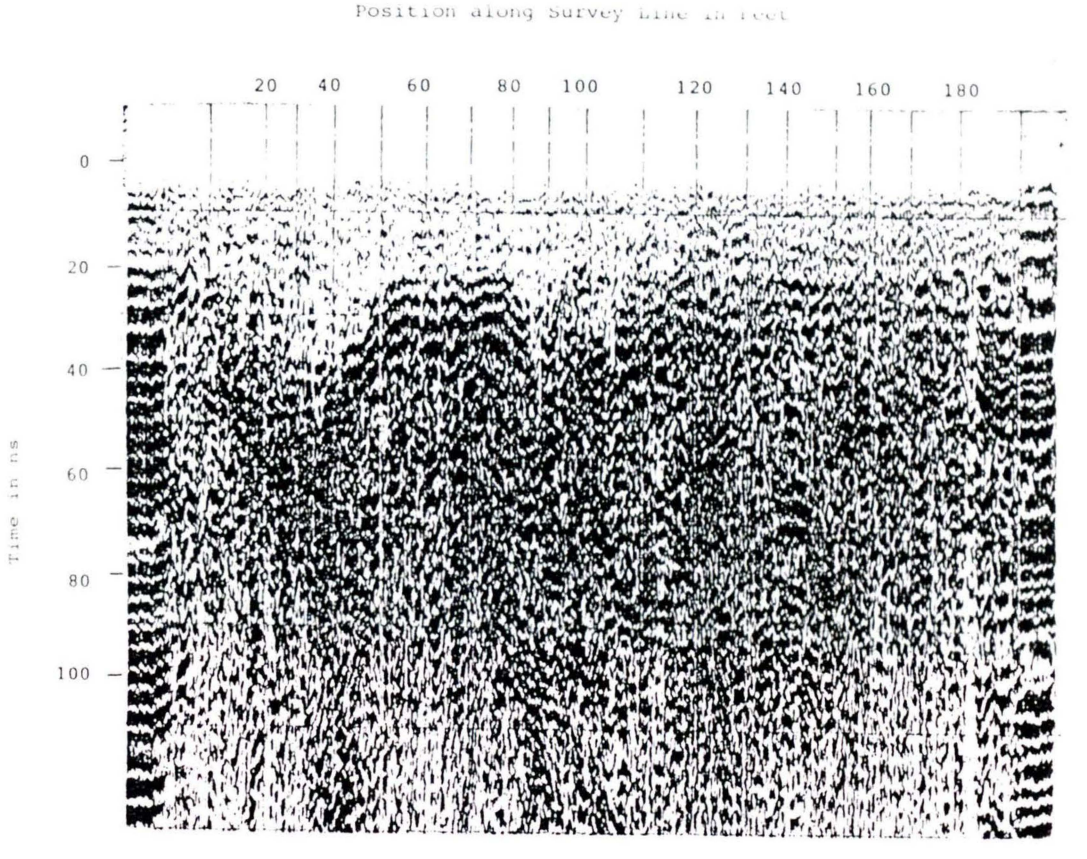


Figure 74. High frequency GPR survey at the Dan Lee site.

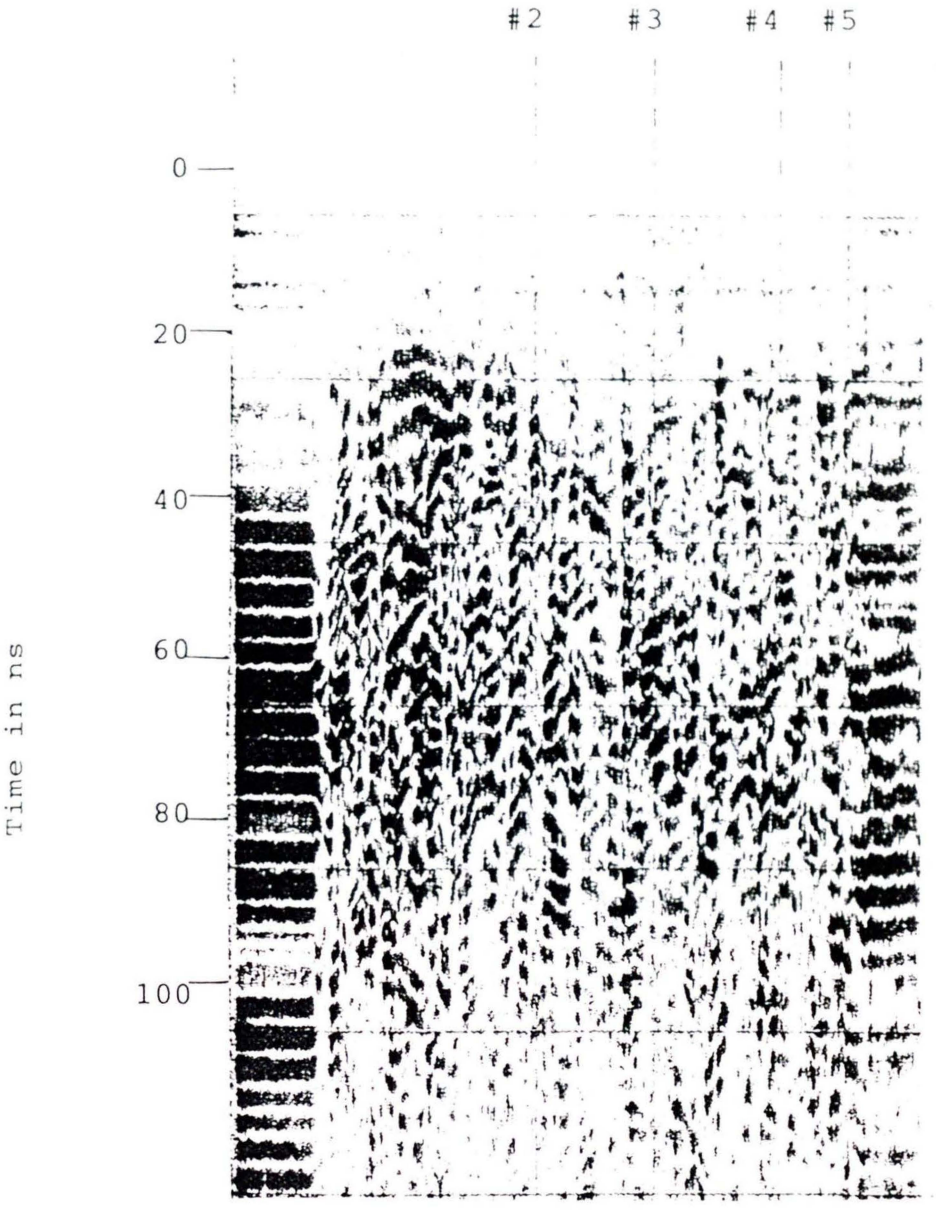


Figure 75. High grequency GPR survey along the lower row of drill holes at the Dan Lee site.

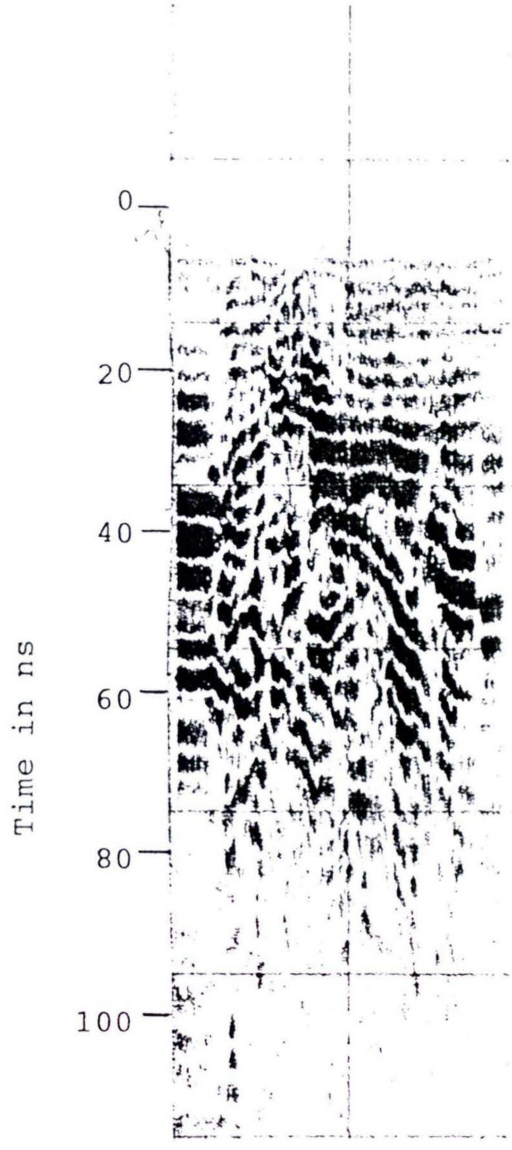


Figure 76. GPR profile across a metal culvert at the Dan Lee site.

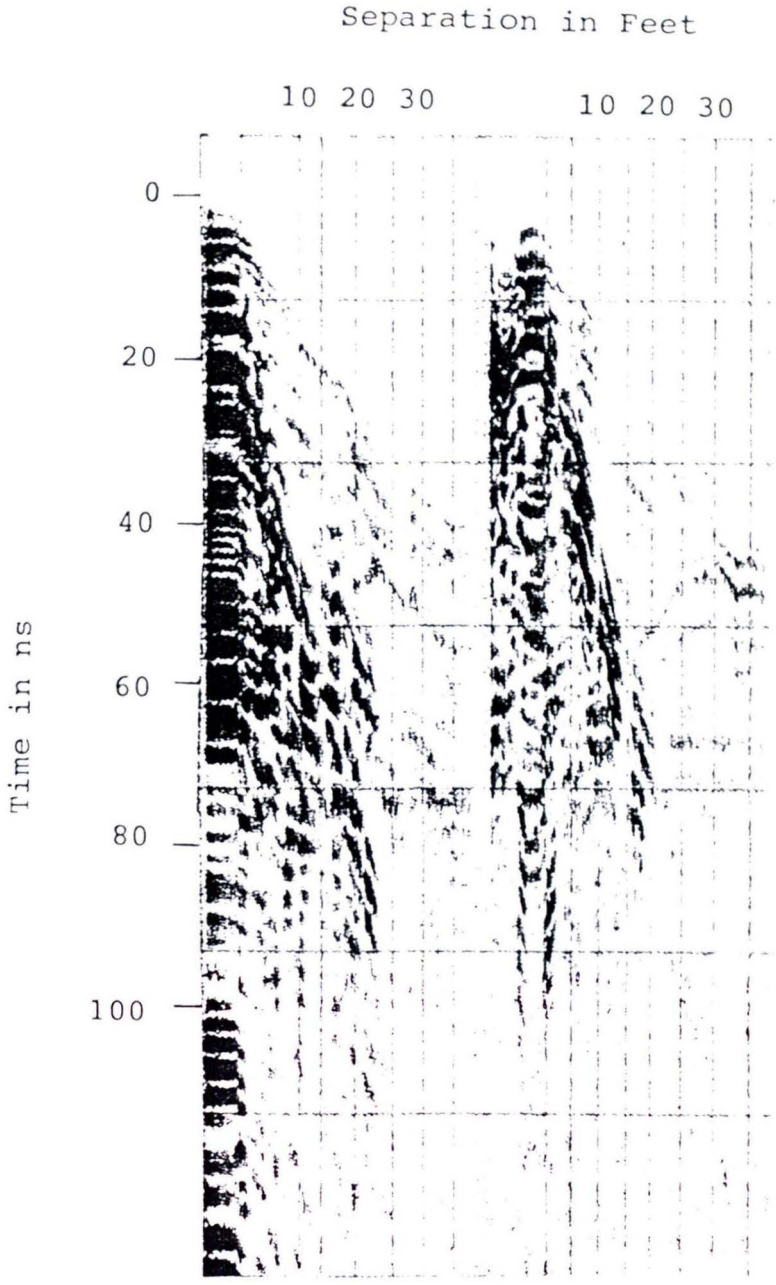


Figure 77. GPR velocity survey at the Lean-To Ridge site.

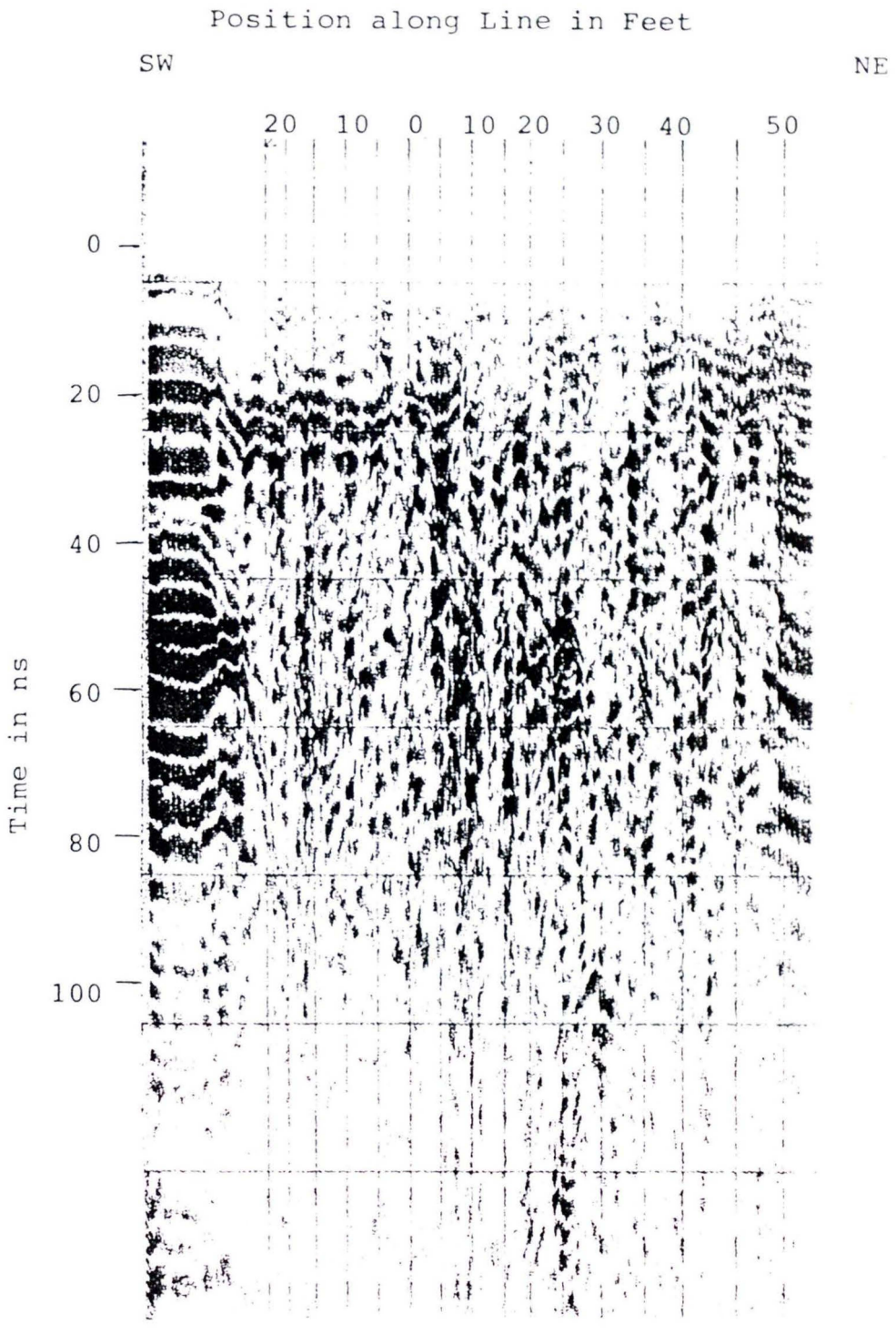


Figure 78. Low frequency GPR section at the Lean-To Ridge site, Line 1.

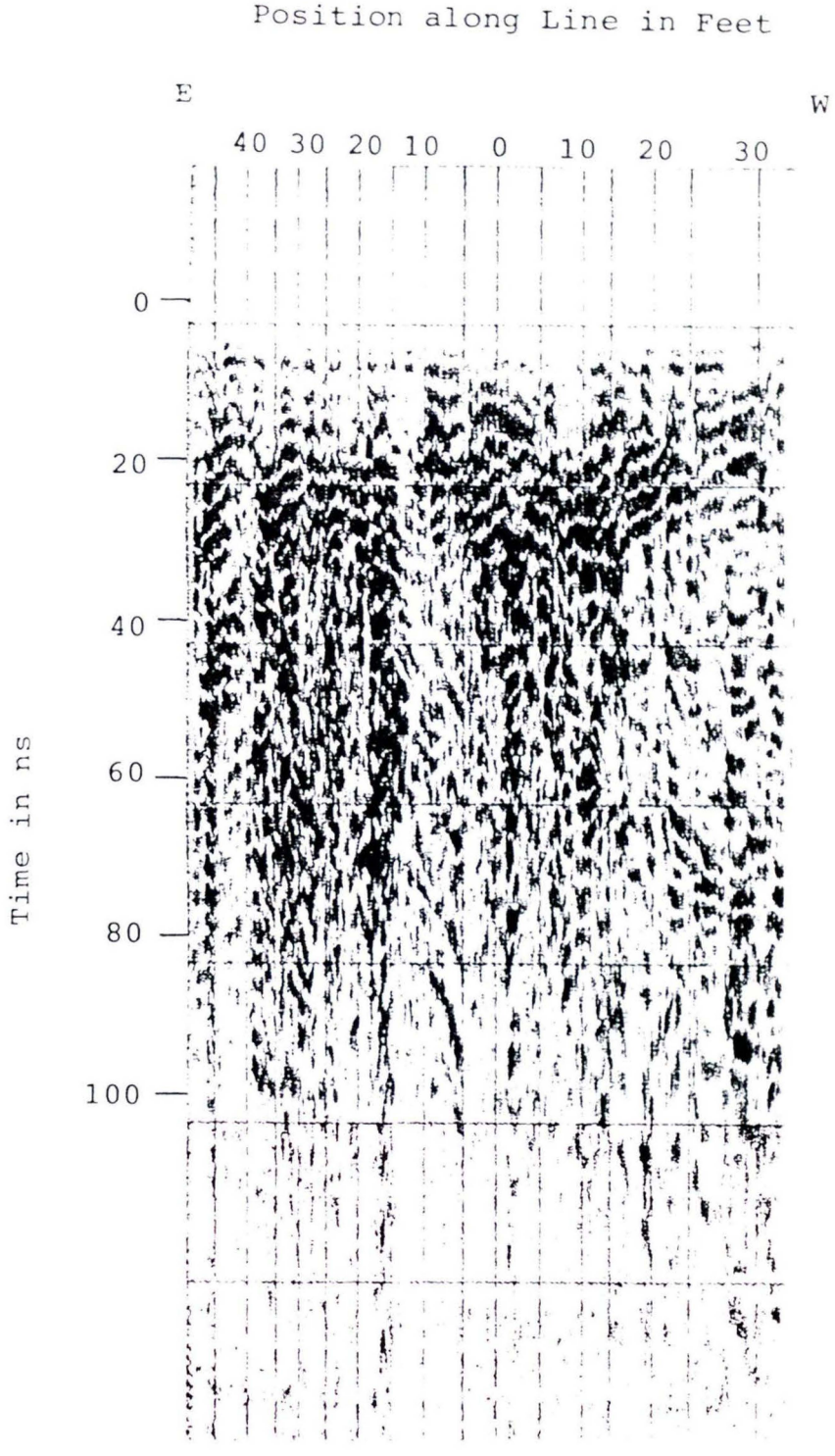


Figure 79. High frequency GPR section at Lean-To Ridge site.

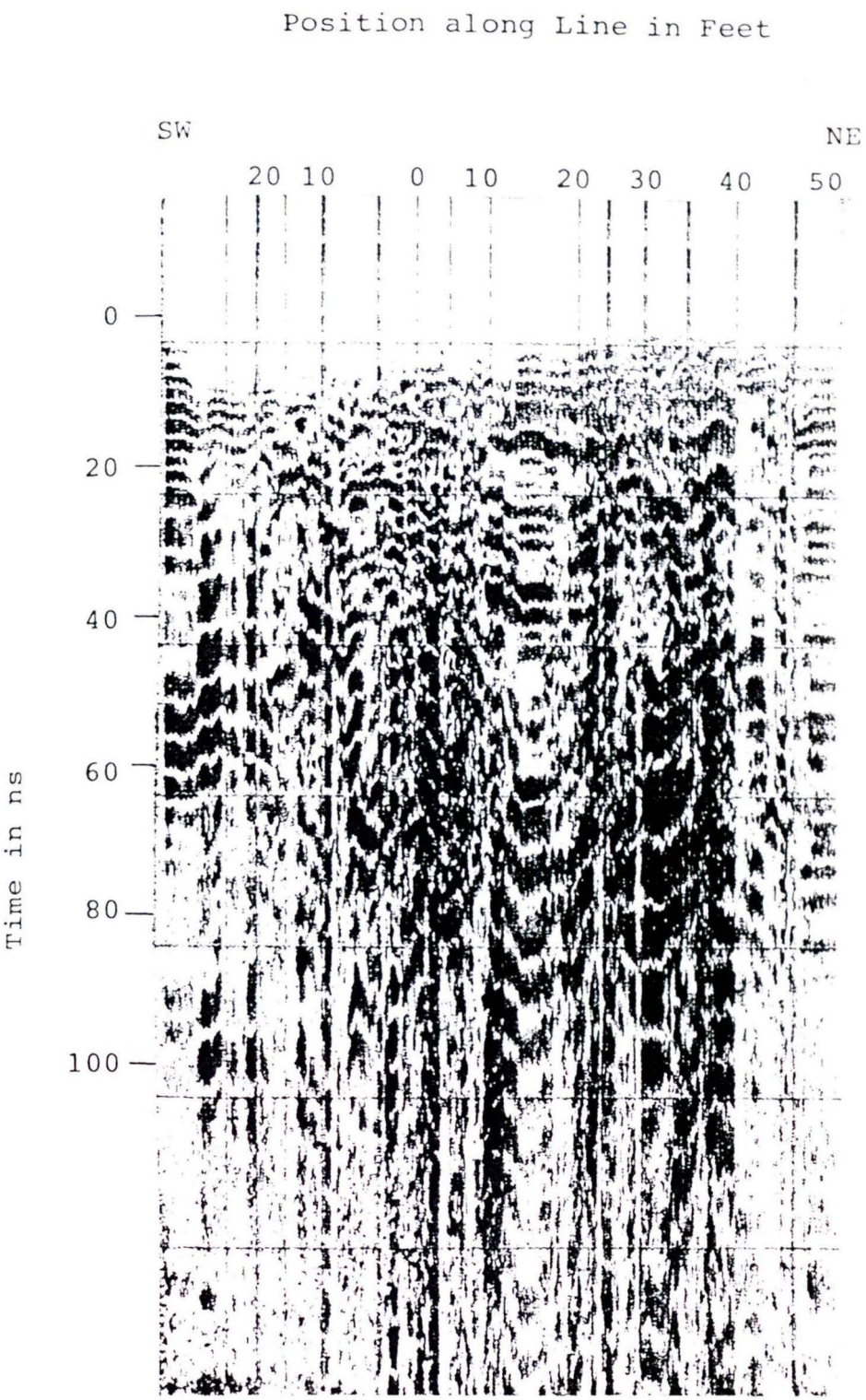


Figure 80. Low frequency GPR profile at Lean-To Ridge, Line 2.

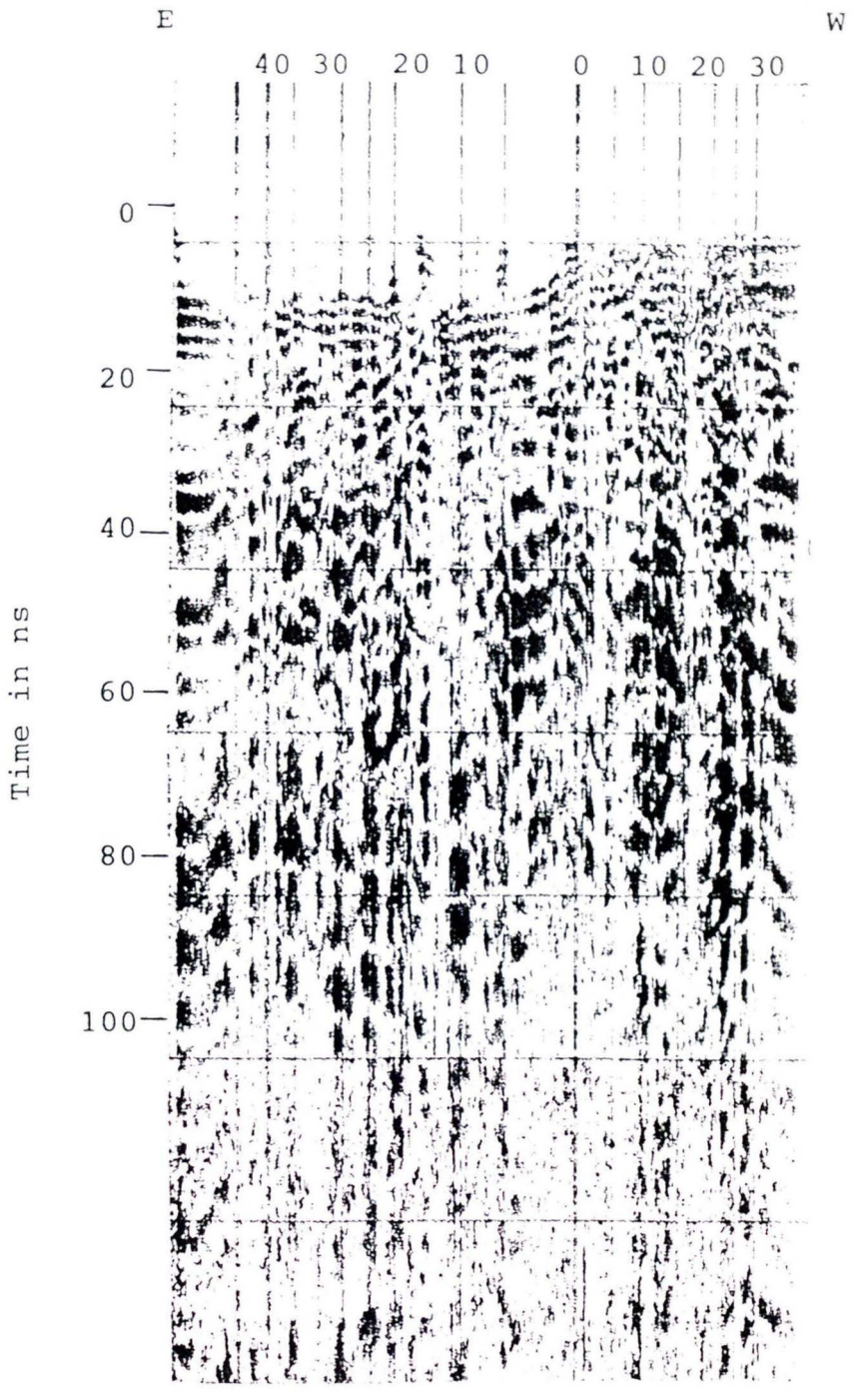


Figure 81. High frequency GPR profile at Lean-To Ridge site, Line 2.

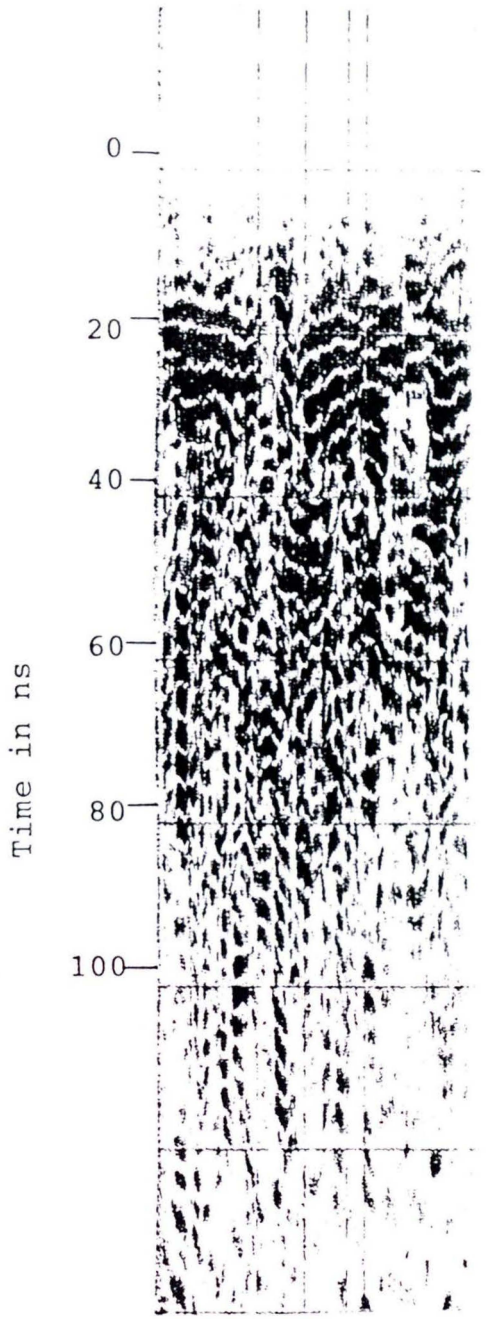


Figure 82. GPR profile over a snow lysimeter at the Lean-To Ridge site.

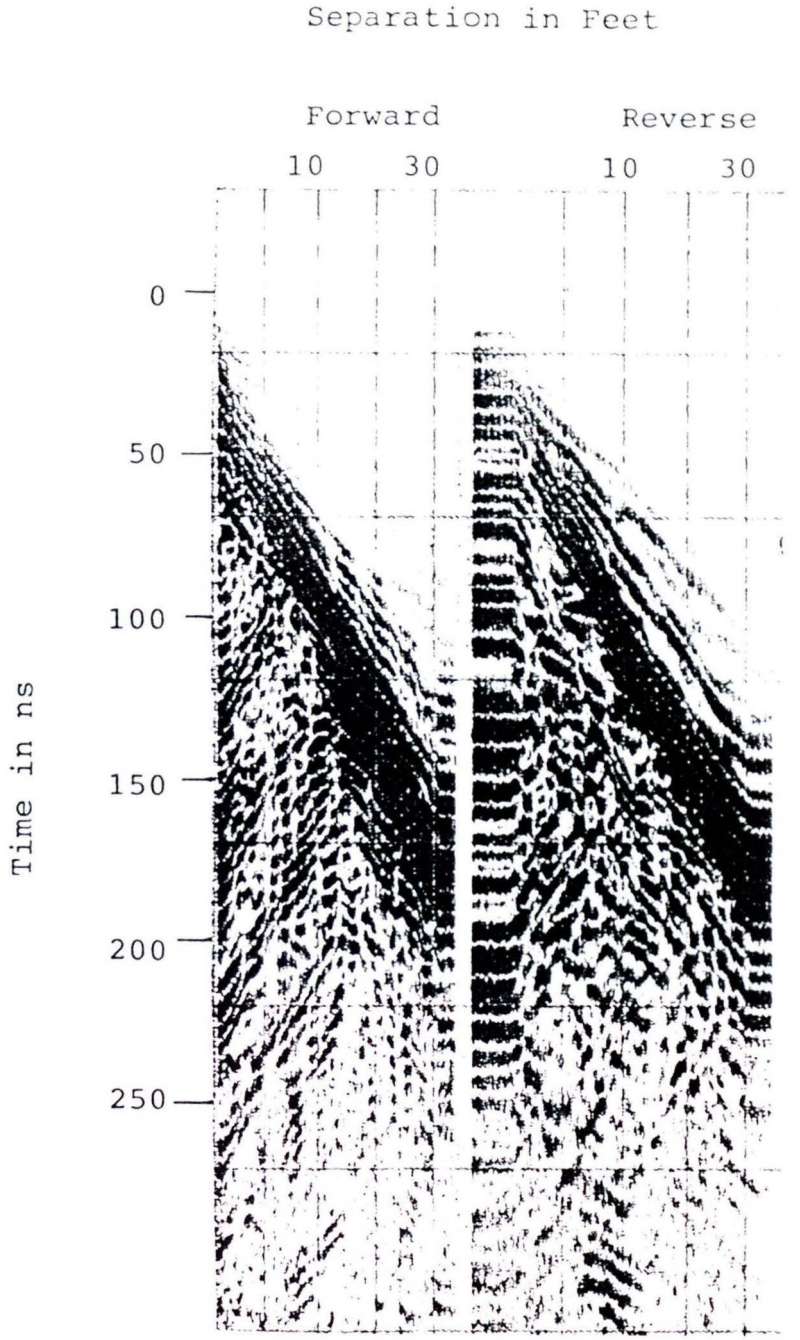


Figure 83. GPR velocity survey on the road above the Lean-To Ridge site.

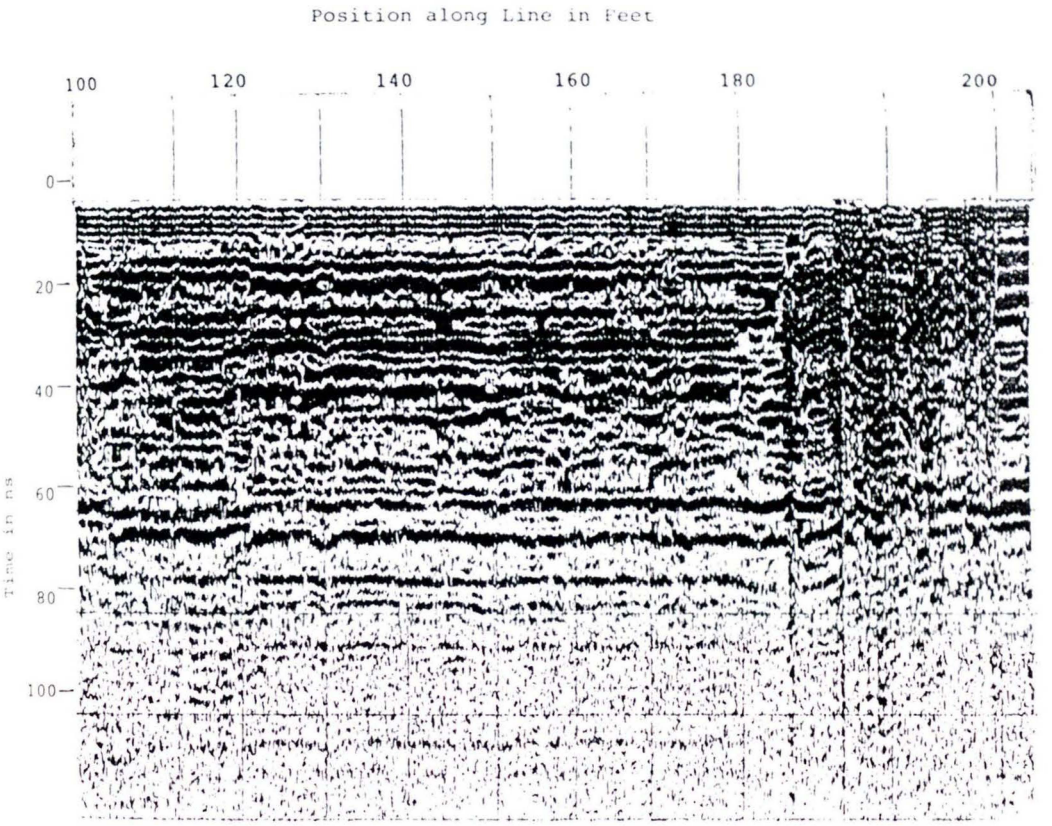


Figure 84. GPR Profile 1 at the Grouse Creek slide.

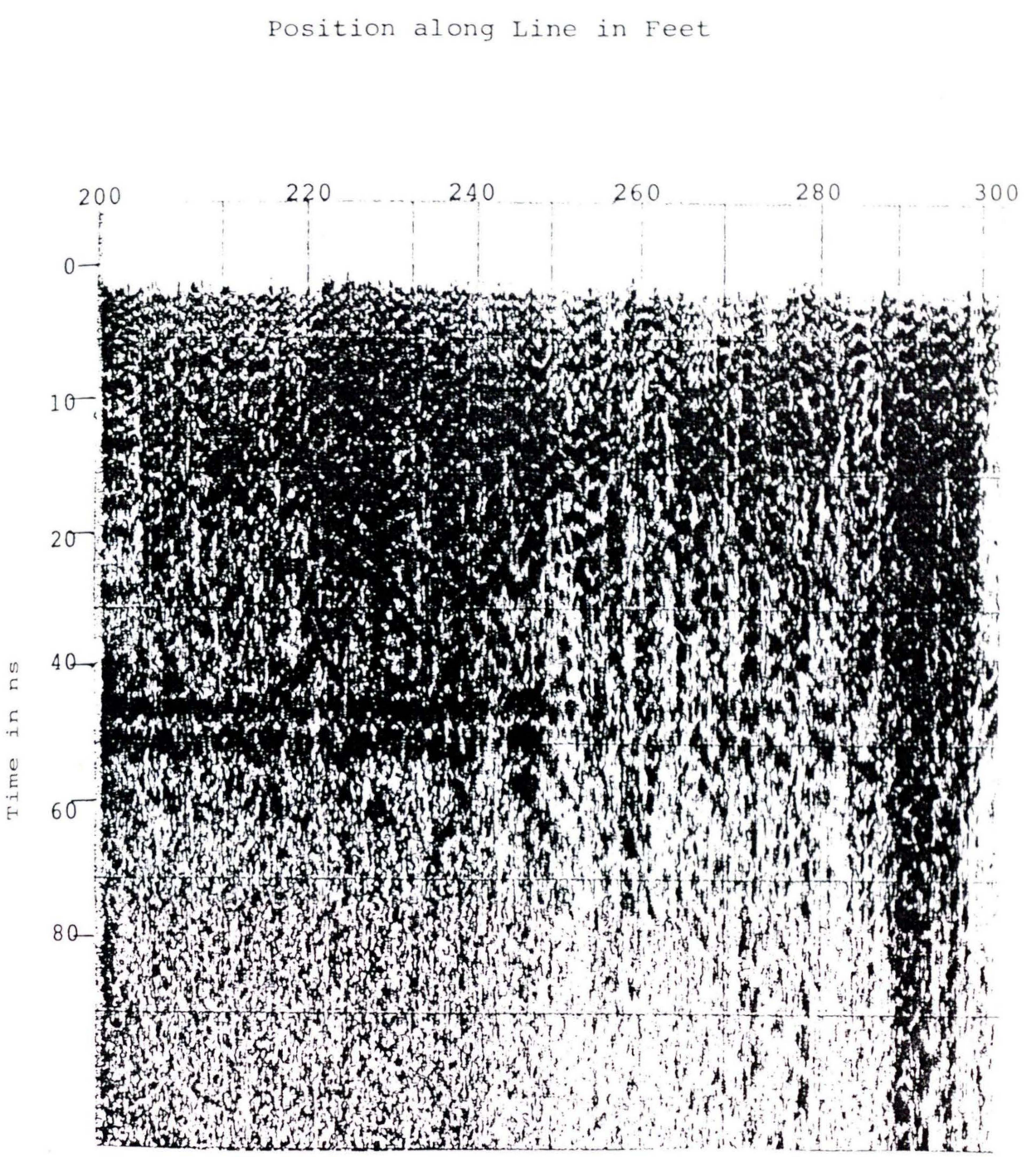


Figure 85. GPR Profile 2 at the Grouse Creek slide, Nezperce National Forest.

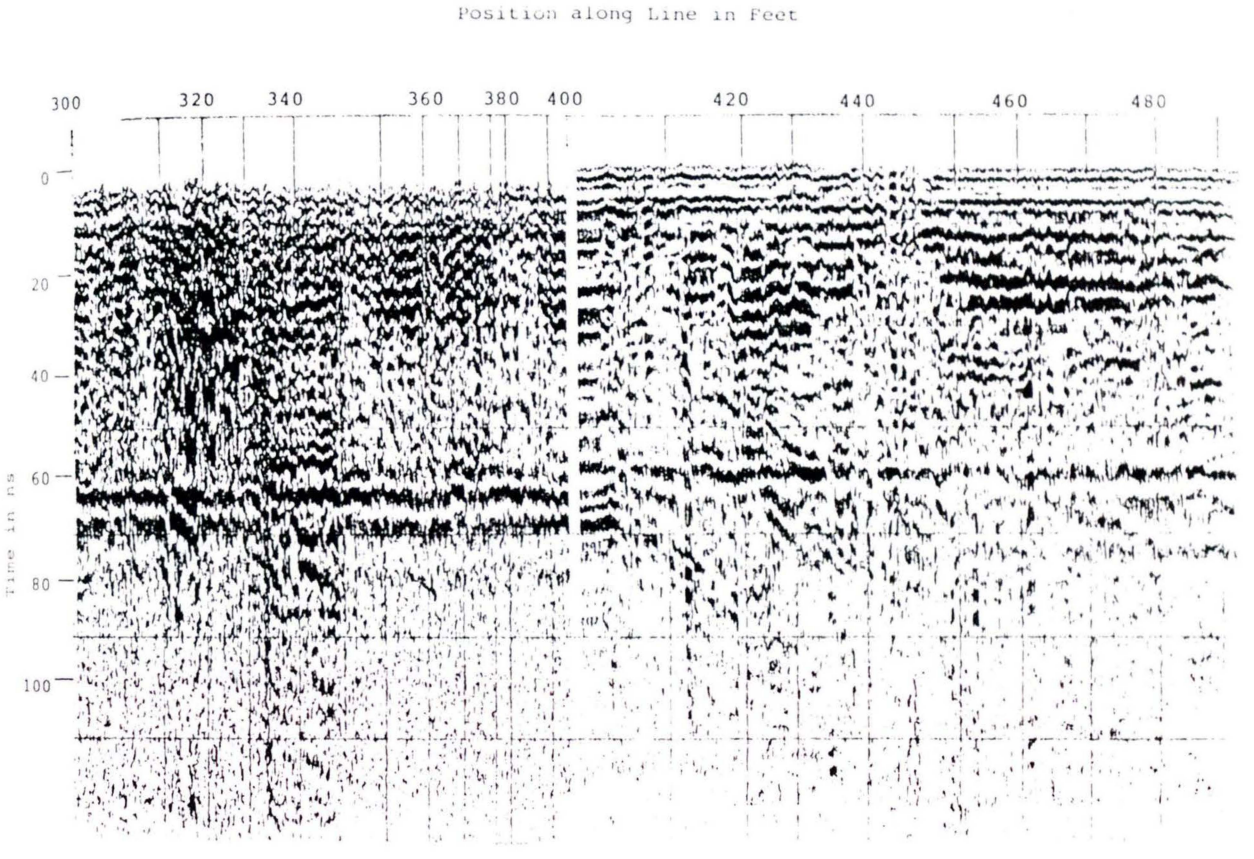


Figure 86. GPR Profile 3 at the Grouse Creek slide, Nezperce National Forest.

Ground penetrating radar (GPR) was evaluated at four National Forest sites as part of this project. The sites selected for evaluation were typical of the geology of northern Idaho, namely, Idaho Batholith intrusions and related border-zone metamorphics,basalt, and carbonates. Three of the sites had been drilled extensively so the subsurface was well understood. The objective was to correlate GPR data with drill hole information to evaluate the usefulness of GPR in determining depth to bedrock, shape of the bedrock surface, soil moisture content, and depth to the water table for slope stability studies.

GPR had reasonable depths of penetration in granitic and metamorphic terrain, perhaps as much as 30 feet, but the reflectors were found difficult to correlate with borehole information. GPR failed to penetrate clayey soil derived from basalt.

Ground-penetrating radar, though widely touted by manufacturers and consultants, has some severe limitations which potential users must consider. These limitations are in 1) ground penetration; 2) instrumentation; 3) field technique, 4) data processing, and 5) interpretation.

GPR is rapidly evolving into a standard tool for engineering geophysics. The method has proven to be of considerable value for the routine location of buried metallic objects (culverts, hazardous waste containers, steel reinforcing rods) and for geological investigations in

special media (ice, peat, coal, massive granite). However, the success of the technique in more common geologic sites is less clear.

If proved useful, GPR would fill an important niche in shallow exploration. It could provide important detail for shallow seismic refraction and electrical resistivity surveys while providing reflection information from interfaces too shallow for routine seismic reflection work.

Ground Penetration

In theory, the penetration of radar waves into the earth is controlled by the conductivity, dielectric constant, magnetic susceptibility of the media and the frequency of the radar. Generally, the higher the electrical conductivity and the frequency, the lower the penetration depth. In soils, penetration depths vary from a few millimeters in clay to 100's of meters in peat.

In practice, for radar reflection surveys, the depth of penetration criteria is more stringent. In order to be detected, a reflection must be sufficiently strong to be distinguished from reverberated air waves and ground waves. Though metallic objects may produce high amplitude reflections, geological interfaces may produce only low amplitude reflections which can easily be lost in the source noise.

Instrumentation

Though a variety of instruments are commercially available, most of the antennas are not suitable for rugged terrain. To get useful results, the antenna must very close to the ground. This effectively limits the method to roads and cleared trails. A need exists for more portable antennas. Presently available antennas are bulky and not at all back-pack portable.

Field Technique

Although known as a fast simple procedure, ground-penetrating radar actually requires the same care and precision as other site investigation techniques if quality results are to be obtained. The great speed of data acquisition allows the possibility of continuous profiling although considerable effort is required to maintain proper surveying. The antenna-to-ground contact must not change along a profile or the results become very incoherent. The signal is strongly disturbed if the antenna is more than a few centimeters above the ground surface. Surveys in bushy terrain--the typical situation in Idaho National Forests--do not produce interpretable results.

Data Processing

Ground-penetrating radar is said to produce a great redundancy of data, but this is actually not the case. Continuous profiling is analogous to 100% coverage in seismic reflection surveys. Even if the antennas are stationary and the signals averaged, no significant

improvement in record quality is produced after the first several repetitions. Some type of common depth point procedure is needed in GPR if records of truly high quality are to be obtained.

Dipping reflectors and diffraction patterns cause horrendous problems for GPR surveys. The huge amount of data collected and the low value of the results (relative to oil company reflection records) suggests that standard seismic reflection processing techniques may not be appropriate for radar surveys. There is a great need for migration software which can operate in near real time as radar data is collected in the field.

Interpretation

GPR interpretation is difficult for a number of reasons: lack of migration (i.e. dipping reflectors do not appear in their correct subsurface positions), and lack of any way to distinguish primary reflections from other noise. Ground and air wave reverberations cause huge noise problems which are impossible to separate from true reflections on radar profiles. Diffraction patterns appear as dipping beds which do not really exist. Without significant improvements in data processing to improve the signal to noise ratio, it is doubtful that GPR can produce sections that are interpretable in terms of shallow geological layering.

PART III

SUMMARY RECOMMENDATIONS

The overall objectives of this study were to test and evaluate geophysical methods for determining soil thickness, configuration of the soil-bedrock interface, and locations of ground water concentration, for use in stability analysis at levels II and III of the landslide hazard evaluation system.

The gruss-covered terrain of central Idaho provided difficulties for many of the geophysical methods evaluated in this study. The seismic refraction method produced excellent information about the depth and shape of the true bedrock interface but no information at all about the more important interface between the relatively impermeable residual soil surface and the overlying porous colluvial soils. This latter interface is far more important for landslide evaluation than the depth to true undisturbed bedrock. We found that simple interpretational procedures can produce satisfactory results for refraction surveys but more complex procedures such as the generalized reciprocal method yield a more holistic picture of the site.

The simplified seismic reflection method showed a definite response to the shallow geology of the test sites, but the records proved to be incoherent. A 22 caliber source and high frequency geophones definitely improved record quality. However, far more sophisticated seismic reflection instrumentation and processing than can be accomplished with a simple engineering seismograph would be required to make use of the seismic reflection method for routine Forest Service work.

The high resolution resistivity method responded too well to variations in the soil moisture content at the test sites. The apparent resistivities were so sensitive to moisture variations that possible anomalies due to the presence of perched water in buried channels were lost in the confusion. The high sensitivity of the resistivity method to moisture content variations could be very useful for landslide studies. However, more instrument development and more sophisticated interpretational procedures are required if the method is ever to be used on a routine basis by the Forest Service for shallow site investigations.

The self potential (SP) method proved a disappointing failure at the generally very dry test sites. It was hoped that simple SP measurements would detect shallow perched ground water moving through buried channels. However, it was found to be very difficult to obtain repeatable readings at the very dry test sites because of the poor electrical contact between the non-polarizing electrodes and the ground surface.

The electromagnetic induction method also failed completely at the test sites to detect ground water concentrations. The very low ionic content of the ground water in these mountain sites in granitic terrain proved to be a poor target for EM methods.

The ground-probing radar method (GPR) was found to have severe limitations as a routine tool at Forest Service site investigation. The major shortcomings are in instrumentation, field technique, data

processing, and interpretation. On the positive side, GPR was found to penetrate several tens of feet in the gruss-covered terrain of central Idaho. Unfortunately, there are no continuous radar targets in this terrain. The contacts between the geological layers are too subtle for radar detection and the perched water concentrations are discontinuous.

RECOMMENDATIONS

1. Seismic refraction remains the most reliable geophysical instrument for routine site investigation at Levels II and III. By using a portable multi-channel seismograph in conjunction with the generalized reciprocal method of interpretation, Forest Service personnel can obtain accurate estimates of the mean and variance of the depth to competent bedrock as well as the shape of the bedrock surface. However, it must be noted that the depth to bedrock may not be the most appropriate value of soil thickness to use in landslide hazard evaluation. The refraction method often does not yield any information on intermediate soil layers or on thin perched water channels.

2. Although the electrical resistivity method and the ground-probing radar method do provide information about the subsurface hydrological environment, the interpretation of these data is too uncertain for routine use in landslide evaluation. At the test sites, we generally could find little correlation between the results of the drill holes and the resistivity or radar results. These methods are also slow and cumbersome in the backcountry. Future innovations in instrument design, field layout, and interpretation are needed if these methods are ever to be useful for landslide hazard evaluations in gruss-covered terrain.

3. The self potential method, the electromagnetic induction method, and the simplified seismic reflection method failed to provide any useful subsurface information at the test sites. Although they may work in other environments, they are useless for landslide hazard evaluation in gruss-covered terrain.

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APPENDIX A

BASIC COMPUTER PROGRAMS

PROGRAM EM9
CONDUCTIVITY BY ELECTROMAGNETIC INDUCTION

This BASIC Program computes the apparent conductivity of a system of horizontal layers over a halfspace for a horizontal loop electromagnetic induction system. Any number of layers can be modelled. The ratio of loop separation to skin depth must be much less than unity for the method to be valid.

The formulas used are shown in Figure 1. More information can be found in McNeill (Electromagnetic terrain conductivity measurement at low induction numbers, Technical Note 6, 1980, Geonics Ltd., Mississauga, Ontario). The constant K in the formulas calibrates the measurement so that it is correct over the earth's surface at a given height. This calibration assumes that all measurements are made at this same height. An example problem is given below. The problem solution and program listing follow.

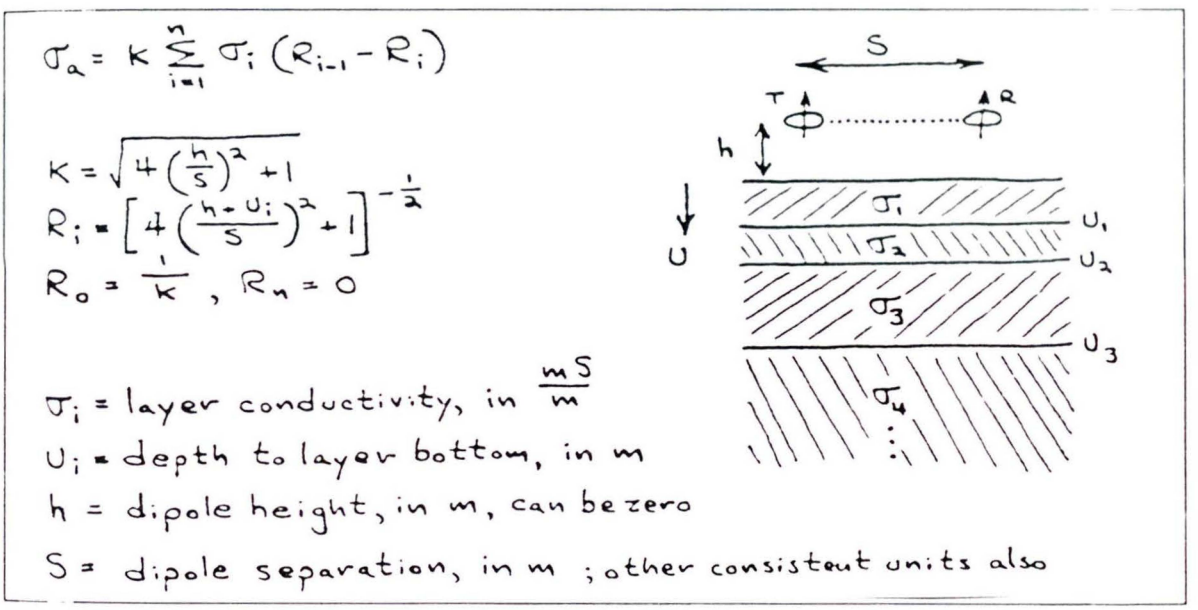
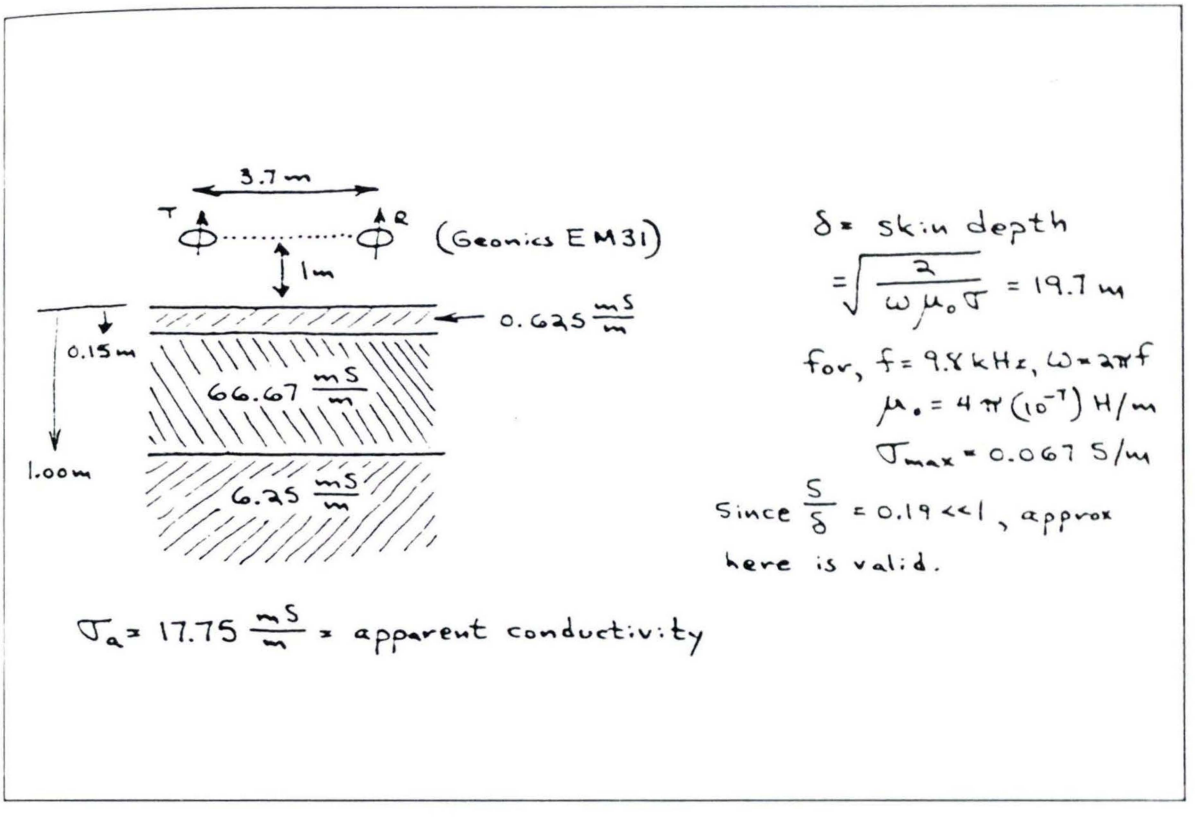


Figure 1. The algorithm used in EM9. After Bevan (MGHCP, 1985).



EXAMPLE 1. Find the apparent conductivity of the layered system shown above. After Bevan (MGHCP, 1985).

PROBLEM SOLUTION

```
SEG PROGRAM EM9 CONDUCTIVITY BY EM INDUCTION

Dipole height (H) in m ?  1
Dipole separation (S) in m ?  3.7
Number of layers including halfspace ?  3
LAYER # 1 Depth to base in m, conductivity in mS/m ?  .15, .625
LAYER # 2 Depth to base in m, conductivity in mS/m ?  1, 66.67
Conductivity of halfspace in ms/m ?  6.25

   17.75 mS/m
```

PROGRAM LISTING

```
'CONDUCTIVITY BY ELECTROMAGNETIC INDUCTION
CLS
PRINT "BASIC PROGRAM  CONDUCTIVITY BY ELECTROMAGNETIC
       INDUCTION"
' This program calculates apparent conductivity for a multilayered
' horizontal system as would be measured by two horizontal
' electromagnetic loops at low induction numbers.  This program is
' a translation of an HP program by B.W. Bevan.
PRINT:INPUT "Hardcopy ? <Y/N>";A$:IF A$= "Y" OR A$="y" THEN P=1
PRINT :IF P THEN LPRINT
IF P THEN LPRINT "CONDUCTIVITY BY EM INDUCTION":LPRINT
PRINT :IF P THEN LPRINT
INPUT "Dipole height (H) in m";H
IF P THEN LPRINT "Dipole height (H) in m ? ";H
INPUT "Dipole separation (S) in m";S
IF P THEN LPRINT "Dipole separation (S) in m ? ";S
INPUT "Number of layers including halfspace";N
IF P THEN LPRINT "Number of layers including halfspace ? ";N
FOR I=1 TO N-1
PRINT "LAYER #";I;
IF P THEN LPRINT "LAYER #";I;
INPUT "Depth to base in m, conductivity in mS/m";V(I),O(I)
IF P THEN LPRINT "Depth to base in m, conductivity in mS/m ? ";V(I),O(I)
NEXT I
INPUT "Conductivity of halfspace in ms/m";O(N)
IF P THEN LPRINT "Conductivity of halfspace in ms/m ? ";O(N)
PRINT : IF P THEN LPRINT
K=SQR(4*(H/S)^2+1)
FOR I=1 TO N-1
R(I)=(4*((H+V(I))/S)^2+1)^(-.5)
NEXT I
R(0)=1/K:R(N)=0
FOR I=1 TO N:SUM=SUM+K*O(I)*(R(I-1)-R(I)):NEXT
PRINT "The apparent conductivity is ";
PRINT USING "######.##";SUM;:PRINT " mS/m"
IF P THEN LPRINT USING "######.##";SUM;:LPRINT " mS/m"
END
```

PROGRAM EM12
TERRAIN CONDUCTIVITY INTERPRETATION

Terrain conductivity can be measured directly by electromagnetic induction. Instruments used for this purpose include the Geonics EM31, EM34-3, and EM38. The coils on the EM31 and EM38 are separated by fixed distances of 3.67 m and 1 m, respectively. These coils may be oriented in the horizontal dipole or vertical dipole modes. The coils of the EM34-3 may be separated by a distance of 10 m, 20 m, or 40 m. Usually, the coils are oriented in the horizontal dipole mode. Below, a BASIC program useful for interpreting terrain conductivity measurements is described.

This program can calculate the following:

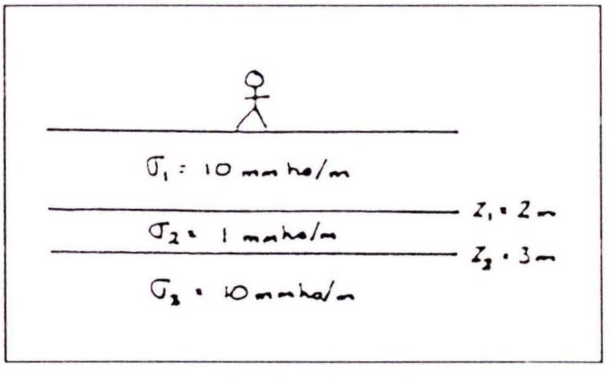
1. The cumulative response function (CRF), for the vertical or horizontal dipole modes. The user must enter the coil separation and the depth.
2. The apparent conductivity of an n-layered system. The user must enter the coil separation, the thickness of each layer, the conductivity of each layer, and the conductivity of the underlying halfspace.
3. Conductivity solution of a one-layer over a halfspace system. For the EM31 and EM38 units, two independent apparent conductivity measurements are made using the vertical and horizontal dipole modes. For the EM34-3 unit, two independent apparent resistivity measurements are made at separations s and 2s. The user must enter the coil separation, assumed thickness, and the two independent apparent resistivity measurements.
4. Thickness of a one-layer over a halfspace system. The user must enter the coil separation, the conductivity of the layer, the conductivity of the halfspace, and either the horizontal or vertical dipole apparent resistivity measurement.

The theory for the above computations may be found in Dunbar (MGHCP, 1985). A number of example problems, their solutions, and the program listing are given below.

EXAMPLE 1. Find the cumulative response function for a depth of 2 m using an EM31 unit in both the vertical and horizontal dipole modes.

SOLUTION:

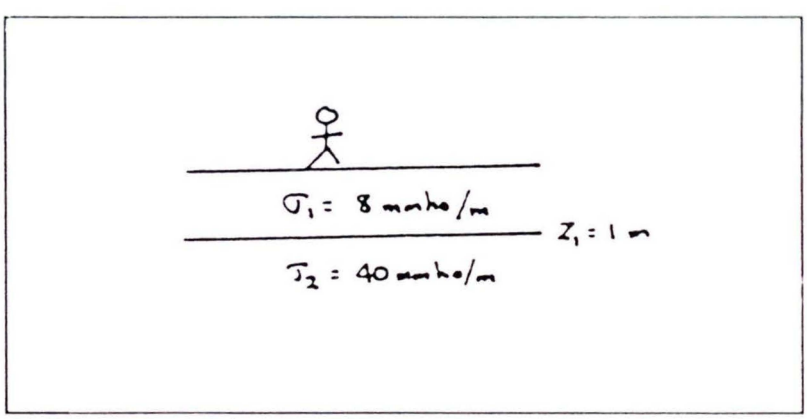
```
Terrain Conductivity Interpretation Programs
based on calculator program by W. Scott Dunbar
BASIC program by Doug Dodge
to continue press any key

          CHOOSE AN OPTION
    CALCULATE CRF                 ENTER: 1
CALC σA (N-LAYERED SYSTEM)        ENTER: 2
1 LAYERED SYSTEM EM31             ENTER: 3
1 LAYERED SYSTEM EM34             ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)     ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE)    ENTER: 6
LEAVE PROGRAM                     ENTER: 7
1
CALCULATE CUMULATIVE RESPONSE FUNCTION
Input dipole separation distance ? 3.67
Input depth of layer ? 2
V(Z)=  .6760582
H(Z)=  .3892444
TO CONTINUE PRESS ANY KEY
```



EXAMPLE 2. Determine the EM31 apparent conductivity for the 2-layered system.

SOLUTION:

```
          CHOOSE AN OPTION
     CALCULATE CRF                 ENTER: 1
CALC σA (N-LAYERED SYSTEM)         ENTER: 2
1 LAYERED SYSTEM EM31              ENTER: 3
1 LAYERED SYSTEM EM34              ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)      ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE)     ENTER: 6
LEAVE PROGRAM                      ENTER: 7
2
APPARENT CONDUCTIVITY OF N LAYERED SYSTEM
Input dipole spacing?  3.67
After last conductivity is entered, enter any value
for thickness of half-space.
Input sigma (mmho/m)?  10
Input depth (meter)?  2
To input another pair press <return>
To see result, press <Esc>.
<ENTER>
Input sigma (mmho/m)?  1
Input depth (meter)?  3
To input another pair press <return>
To see result, press <Esc>.
<ENTER>
Input sigma (mmho/m)?  10
Input depth (meter)?  1
To input another pair press <return>
To see result, press <Esc>.
<ESC>
Apparent conductivity (vertical dipole) =  8.611631
Apparent conductivity (horizontal dipole) =  9.031058
```



EXAMPLE 3. Determine the apparent conductivity of the single-layer system above assuming a coil spacing of 10 m.

SOLUTION:

```
          CHOOSE AN OPTION
    CALCULATE CRF                ENTER: 1
CALC σA (N-LAYERED SYSTEM)       ENTER: 2
1 LAYERED SYSTEM EM31            ENTER: 3
1 LAYERED SYSTEM EM34            ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)    ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE)   ENTER: 6
LEAVE PROGRAM                    ENTER: 7
2
APPPARENT CONDUCTIVITY OF N LAYERED SYSTEM
Input dipole spacing?  10
After last conductivity is entered, enter any value
for thickness of half-space.
Input sigma (mmho/m)?  8
Input depth (meter)?  1
To input another pair press <return>
To see result, press <Esc>.
<ENTER>
Input sigma (mmho/m)?  40
Input depth (meter)?  1
To input another pair press <return>
To see result, press <Esc>.
<ESC>
Apparent conductivity (vertical dipole) =  39.37858
Apparent conductivity (horizontal dipole) =  34.23373
TO CONTINUE PRESS ANY KEY
```

EXAMPLE 4. Given a thickness of 3 m, an EM31 vertical dipole apparent conductivity of 14.4 mmho/m, and horizontal dipole apparent conductivity of 21.6 mmho/m, find the conductivity of the layer and the halfspace.

SOLUTION:

```
          CHOOSE AN OPTION
    CALCULATE CRF                ENTER: 1
CALC σA (N-LAYERED SYSTEM)       ENTER: 2
1 LAYERED SYSTEM EM31            ENTER: 3
1 LAYERED SYSTEM EM34            ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)    ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE)   ENTER: 6
LEAVE PROGRAM                    ENTER: 7
3
SOLUTION FOR σ1 AND σ2 USING EM31 DATA
INPUT APPARENT CONDUCTIVITY USING HORIZONTAL DIPOLE ? 21.6
INPUT APPARENT CONDUCTIVITY USING VERTICAL DIPOLE ? 14.4
Input depth to bottom of layer ?  3
Input coil separation ?  3.67
σ1 =  30.0401
σ2 =  6.645203E-02
TO CONTINUE PRESS ANY KEY
```

EXAMPLE 5. Given a thickness of 5 m, and EM34-3 readings of 21.3 mmho/m and 27.8 mmho/m at coil separations of 10 m and 20 m, respectively, find the conductivity of the layer and halfspace.

SOLUTION:

```
          CHOOSE AN OPTION
    CALCULATE CRF              ENTER: 1
CALC σA (N-LAYERED SYSTEM)     ENTER: 2
1 LAYERED SYSTEM EM31          ENTER: 3
1 LAYERED SYSTEM EM34          ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)  ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE) ENTER: 6
LEAVE PROGRAM                  ENTER: 7
4
SOLUTION FOR σ1 AND σ2 USING EM34 DATA
Input depth to bottom of layer?  5
Input coil separation?       10
INPUT APPARENT CONDUCTIVITY USING SPACING 'S'?  21.3
INPUT APPARENT CONDUCTIVITY USING SPACING '2S'?  27.8
σ1 =  8.09039
σ2 =  39.98121
TO CONTINUE PRESS ANY KEY
```

EXAMPLE 6. Given a layer conductivity of 30 mmho/m, a halfspace conductivity of 0.1 mmho/m, and an EM31 vertical dipole conductivity of 14.4 mmho/m, find the thickness of the layer.

SOLUTION:

```
          CHOOSE AN OPTION
    CALCULATE CRF              ENTER: 1
CALC σA (N-LAYERED SYSTEM)     ENTER: 2
1 LAYERED SYSTEM EM31          ENTER: 3
1 LAYERED SYSTEM EM34          ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)  ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE) ENTER: 6
LEAVE PROGRAM                  ENTER: 7
5
FIND Z1 GIVEN σA MEASURED BY VERTICAL DIPOLES
INPUT DIPOLE SPACING (EM31)?              3.67
INPUT σ1?  30
INPUT σ2?  .1
INPUT APPARENT CONDUCTIVITY?  14.4
Z1 =  3.000442
TO CONTINUE PRESS ANY KEY
```

EXAMPLE 7. Given a coil separation of 10 m, a layer conductivity of 8.1 mmho/m, a halfspace conductivity of 40 mmho/m, and a horizontal dipole apparent conductivity of 21.3 mmho/m, find the thickness of the layer.

SOLUTION:

```
          CHOOSE AN OPTION
    CALCULATE CRF                ENTER: 1
CALC σA (N-LAYERED SYSTEM)       ENTER: 2
1 LAYERED SYSTEM EM31            ENTER: 3
1 LAYERED SYSTEM EM34            ENTER: 4
FIND Z GIVEN σA (VERT DIPOLE)    ENTER: 5
FIND Z GIVEN σA (HORIZ DIPOLE)   ENTER: 6
LEAVE PROGRAM                    ENTER: 7
6
FIND Z1 GIVEN σA MEASURED BY HORIZONTAL DIPOLES
INPUT DIPOLE SPACING (EM34)?  10
INPUT σ1?  8.100001
INPUT σ2?  40
INPUT APPARENT CONDUCTIVITY?  21.3
Z1 =  5.007386
TO CONTINUE PRESS ANY KEY
```

PROGRAM LISTING

```
      ' EM12   TERRAIN CONDUCTIVITY INTERPRETATION
      CLS
      PRINT "SEG PROGRAM EM12   TERRAIN CONDUCTIVITY INTERPRETATION"
      PRINT:INPUT "Hardcopy <Y/N>";A$: IF A$="Y" OR A$="y" THEN Q=1
      PRINT:IF Q THEN LPRINT
      '*********** write opening screen ***************
      CLS
      LOCATE 4,30:COLOR 0,7:PRINT " EM-12 ":COLOR 7,0
      IF Q THEN LPRINT " EM-12 "
      LOCATE 7,20:PRINT "Terrain Conductivity Interpretation Programs"
      IF Q THEN LPRINT "Terrain Conductivity Interpretation Programs"
      LOCATE 10,20:PRINT "based on calculator program by W. Scott Dunbar"
      IF Q THEN LPRINT "based on calculator program by W. Scott Dunbar"
      LOCATE 11,20:PRINT "BASIC program by Doug Dodge"
      IF Q THEN LPRINT "BASIC program by Doug Dodge"
      LOCATE 15,20:PRINT "to continue press any key"
      IF Q THEN LPRINT "to continue press any key"
180   K$=INKEY$:IF K$="" GOTO 180
      IF Q THEN LPRINT K$
      '************************************************
      DIM SIG(10),Z(10)
      DEF FNV(Z,S)=S/SQR(4*Z^2+S^2)
      DEF FNH(Z,S)=(SQR(4*Z^2+S^2)-2*Z)/S
      KEY OFF
      FOR I=1 TO 10: KEY I,"":NEXT
260   CLS:IF Q THEN LPRINT:LPRINT
      R=2:C1=5: C2345=5: C6=34: INC1=3: INC2=1
      LOCATE R,C2345
      LOCATE R,C1
      COLOR 0,7
      PRINT "           CHOOSE AN OPTION           "
      IF Q THEN LPRINT "           CHOOSE AN OPTION           "
      COLOR 7,0
      R=R+INC1
      LOCATE R,C2345
      PRINT "     CALCULATE CRF             ENTER: ";:COLOR 15,0:PRINT          "1":COLOR 7
      IF Q THEN LPRINT "     CALCULATE CRF             ENTER: ";"1"
```

```
      R=R+INC2
      LOCATE R,C2345
      PRINT "CALC σA (N-LAYERED SYSTEM)     ENTER: ";:COLOR 15,0:PRINT          "2":COLOR 7
      IF Q THEN LPRINT "CALC σA (N-LAYERED SYSTEM)     ENTER: ";"2"
      R=R+INC2
      LOCATE R,C2345
      PRINT "1 LAYERED SYSTEM EM31          ENTER: ";:COLOR 15,0:PRINT          "3":COLOR 7
      IF Q THEN LPRINT "1 LAYERED SYSTEM EM31          ENTER: ";"3"
      R=R+INC2
      LOCATE R,C2345
      PRINT "1 LAYERED SYSTEM EM34          ENTER: ";:COLOR 15,0:PRINT          "4":COLOR 7
      IF Q THEN LPRINT "1 LAYERED SYSTEM EM34          ENTER: ";"4"
      R=R+INC2
      LOCATE R,C2345
      PRINT "FIND Z GIVEN σA (VERT DIPOLE)  ENTER: ";:COLOR 15,0:PRINT          "5":COLOR 7
      IF Q THEN LPRINT "FIND Z GIVEN σA (VERT DIPOLE)  ENTER: ";"5"
      R=R+INC2
      LOCATE R,C2345
      PRINT "FIND Z GIVEN σA (HORIZ DIPOLE) ENTER: ";:COLOR 15,0:PRINT          "6":COLOR 7
      IF Q THEN LPRINT "FIND Z GIVEN σA (HORIZ DIPOLE) ENTER: ";"6"
      R=R+INC2
      LOCATE R,C2345
      PRINT "LEAVE PROGRAM                  ENTER: ";:COLOR 15,0:PRINT          "7":COLOR 7
      IF Q THEN LPRINT "LEAVE PROGRAM                  ENTER: ";"7"
      R =R+INC2+1
      LOCATE R,5
      LOCATE R,C6+12,1,0,7
650   K$=INKEY$
      IF K$="" GOTO 650
      IF Q THEN LPRINT K$:LPRINT
      IF K$="1"  THEN GOTO 760
      IF K$="2"  THEN GOTO 930
      IF K$="3"  THEN GOTO 1140
      IF K$="4"  THEN GOTO 1360
      IF K$="5"  THEN GOTO 1580
      IF K$="6"  THEN GOTO 1780
      IF K$="7"  THEN GOTO 2270
      GOTO 650
760 CLS
      PRINT "CALCULATE CUMULATIVE RESPONSE FUNCTION"
      IF Q THEN LPRINT "CALCULATE CUMULATIVE RESPONSE FUNCTION"
      INPUT "input dipole separation distance ",S
      IF Q THEN LPRINT "Input dipole separation distance ?";S
      INPUT "input depth of layer ",Z
      IF Q THEN LPRINT "Input depth of layer ?";Z
      PRINT "V(Z)= ",FNV(Z,S)
      IF Q THEN LPRINT "V(Z)= ";FNV(Z,S)
      PRINT "H(Z)= ",FNH(Z,S)
      IF Q THEN LPRINT "H(Z)= ";FNH(Z,S)
      PRINT "TO CONTINUE PRESS ANY KEY"
      IF Q THEN LPRINT "TO CONTINUE PRESS ANY KEY"
890   K$=INKEY$:IF K$="" GOTO 890
      IF Q THEN LPRINT K$
      GOTO 260
      '.................................
930   CLS:PRINT "APPPARENT CONDUCTIVITY OF N LAYERED SYSTEM"
      IF Q THEN LPRINT:LPRINT "APPPARENT CONDUCTIVITY OF N LAYERED SYSTEM"
      INPUT "input dipole spacing ",S
      IF Q THEN LPRINT "Input dipole spacing? ";S
      GOSUB 2060
      SUM=0:SUM2=0
      FOR J=1 TO N-1
      SUM=SUM+(SIG(J)-SIG(J+1))*FNV(Z(J),S)
      SUM2=SUM2+(SIG(J)-SIG(J+1))*FNH(Z(J),S)
      NEXT
      SIGAV=SIG(1)-SUM
      SIGAH=SIG(1)-SUM2
      PRINT "apparent conductivity (vertical dipole) = ",SIGAV
      IF Q THEN LPRINT "Apparent conductivity (vertical dipole) = ";SIGAV
```

```
      PRINT "apparent conductivity (horizontal dipole) = ",SIGAH
      IF Q THEN LPRINT "Apparent conductivity (horizontal dipole) = ";SIGAH
      PRINT     "TO CONTINUE PRESS ANY KEY"
      IF Q THEN LPRINT "TO CONTINUE PRESS ANY KEY":LPRINT
1110  K$=INKEY$:IF K$="" GOTO 1110
      GOTO 260
      '.....................................
1140  CLS:PRINT "SOLUTION FOR σ1 AND σ2 USING EM31 DATA"
      IF Q THEN LPRINT "SOLUTION FOR σ1 AND σ2 USING EM31 DATA"
      INPUT "INPUT APPARENT CONDUCTIVITY USING HORIZONTAL DIPOLE ",M2
      IF Q THEN LPRINT"INPUT APPARENT CONDUCTIVITY USING HORIZONTAL DIPOLE                ?";M2
      INPUT "INPUT APPARENT CONDUCTIVITY USING VERTICAL DIPOLE ",M1
      IF Q THEN LPRINT "INPUT APPARENT CONDUCTIVITY USING VERTICAL DIPOLE                 ?";M1
      INPUT "input depth to bottom of layer ",Z
      IF Q THEN LPRINT "Input depth to bottom of layer ? ";Z
      INPUT "input coil separation ",S
      IF Q THEN LPRINT "Input coil separation ? ";S
      R1=FNV(Z,S):R2=FNH(Z,S)
      SIG1=(M1*R2-M2*R1)/(R2-R1)
      SIG2=SIG1+(M2-M1)/(R2-R1)
      PRINT "σ1 = ",SIG1
      IF Q THEN LPRINT "σ1 = ";SIG1
      PRINT "σ2 = ",SIG2
      IF Q THEN LPRINT "σ2 = ";SIG2
      PRINT "TO CONTINUE PRESS ANY KEY"
      IF Q THEN LPRINT "TO CONTINUE PRESS ANY KEY" :LPRINT
1330  K$=INKEY$:IF K$="" GOTO 1330
      GOTO 260
      '.....................................
1360  CLS:PRINT "SOLUTION FOR σ1 AND σ2 USING EM34 DATA"
      IF Q THEN LPRINT "SOLUTION FOR σ1 AND σ2 USING EM34 DATA"
      INPUT "input depth to bottom of layer ",Z
      IF Q THEN LPRINT "Input depth to bottom of layer? ";Z
      INPUT "input coil separation ",S
      IF Q THEN LPRINT "Input coil separation? ",S
      INPUT "INPUT APPARENT CONDUCTIVITY USING SPACING 'S' ",M1
      IF Q THEN LPRINT "INPUT APPARENT CONDUCTIVITY USING SPACING 'S'? ";M1
      INPUT "INPUT APPARENT CONDUCTIVITY USING SPACING '2S' ",M2
      IF Q THEN LPRINT "INPUT APPARENT CONDUCTIVITY USING SPACING '2S'?          ";M2
      R1=FNH(Z,S):R2=FNH(Z,2*S)
      SIG1=(M1*R2-M2*R1)/(R2-R1)
      SIG2=SIG1+(M2-M1)/(R2-R1)
      PRINT "σ1 = ",SIG1
      IF Q THEN LPRINT "σ1 = ";SIG1
      PRINT "σ2 = ",SIG2
      IF Q THEN LPRINT "σ2 = ";SIG2
      PRINT "TO CONTINUE PRESS ANY KEY"
      IF Q THEN LPRINT "TO CONTINUE PRESS ANY KEY":LPRINT
1550  K$=INKEY$:IF K$="" GOTO 1550
      GOTO 260
      '.....................................
1580  CLS:PRINT "FIND Z1 GIVEN σA MEASURED BY VERTICAL DIPOLES"
      IF Q THEN LPRINT "FIND Z1 GIVEN σA MEASURED BY VERTICAL DIPOLES"
      INPUT "INPUT DIPOLE SPACING (EM31) ",S
      IF Q THEN LPRINT "INPUT DIPOLE SPACING (EM31)? ",S
      INPUT "INPUT σ1 ",SIG1
      IF Q THEN LPRINT "INPUT σ1? ";SIG1
      INPUT "INPUT σ2 ",SIG2
      IF Q THEN LPRINT "INPUT σ2? ";SIG2
      INPUT "INPUT APPARENT CONDUCTIVITY ",SIGA
      IF Q THEN LPRINT "INPUT APPARENT CONDUCTIVITY? ";SIGA
      W=(SIGA-SIG1)/(SIG2-SIG1)
      IF W<0 OR W>1 THEN CLS:PRINT "ERROR!":IF Q<>1 THEN GOTO 1730
         ELSE LPRINT"ERROR!":GOTO 1730
      Z1=S/2*SQR(1/W^2-1)
      PRINT "Z1 = ",Z1
      IF Q THEN LPRINT "Z1 = ";Z1
1730  PRINT "TO CONTINUE PRESS ANY KEY"
      IF Q THEN LPRINT "TO CONTINUE PRESS ANY KEY":LPRINT
```

```
1750  K$=INKEY$:IF K$="" GOTO 1750
      GOTO 260
      '.....................................
1780  CLS:PRINT "FIND Z1 GIVEN σA MEASURED BY HORIZONTAL DIPOLES"
      IF Q THEN LPRINT "FIND Z1 GIVEN σA MEASURED BY HORIZONTAL DIPOLES"
      DEF FNZ(Z,S,W)=SQR(4*Z^2+S^2)-2*Z-S*W
      INPUT "INPUT DIPOLE SPACING (EM34) ",S
      IF Q THEN LPRINT "INPUT DIPOLE SPACING (EM34)? ";S
      INPUT "INPUT σ1 ",SIG1
      IF Q THEN LPRINT "INPUT σ1? ";SIG1
      INPUT "INPUT σ2 ",SIG2
      IF Q THEN LPRINT "INPUT σ2? ";SIG2
      INPUT "INPUT APPARENT CONDUCTIVITY ",SIGA
      IF Q THEN LPRINT "INPUT APPARENT CONDUCTIVITY? ";SIGA
      W=(SIGA-SIG1)/(SIG2-SIG1)
      IF W<0 OR W>1 THEN CLS:PRINT "ERROR!":IF Q <> 1 THEN GOTO 2000 ELSE        LPRINT "ERROR":
GOTO 2000
      ZMIN=0:ZMAX=10000
1920  ZMID=(ZMIN+ZMAX)/2
      IF ABS(ZMIN-ZMID)<.001 THEN ANS=ZMID:GOTO 1970
      A=FNZ(ZMIN,S,W):B=FNZ(ZMID,S,W)
      IF A*B >0 THEN ZMIN=ZMID ELSE ZMAX=ZMID
      GOTO 1920
1970  PRINT "Z1 = ",ANS
      IF Q THEN LPRINT "Z1 = ";ANS
      '
2000  PRINT "TO CONTINUE PRESS ANY KEY"
      IF Q THEN LPRINT "TO CONTINUE PRESS ANY KEY":LPRINT
2020  K$=INKEY$:IF K$="" GOTO 2020
      GOTO 260
      '.....................................
      '
02060 ' subroutine to get data from keyboard
      PRINT "After last conductivity is entered, enter any value"
      IF Q THEN LPRINT "After last conductivity is entered, enter any            value"
      PRINT "for thickness of half-space."
      IF Q THEN LPRINT "for thickness of half-space."
      N=1
2120  LOCATE 18,5:PRINT SPACE$(50)
      LOCATE 19,5:PRINT SPACE$(50)
      LOCATE 5,21:PRINT SPACE$(20):LOCATE 5,10:INPUT "input sigma (mmho/m)               ",SIG(N)
      IF Q THEN LPRINT "Input sigma (mmho/m)? ";SIG(N)
      LOCATE 6,22:PRINT SPACE$(20):LOCATE 6,10:INPUT "input depth (meter)                ",Z(N)
      IF Q THEN LPRINT "Input depth (meter)? ";Z(N)
      N=N+1
      LOCATE 18,5:COLOR 0,7:PRINT "To input another pair, press <return>"
      IF Q THEN LPRINT "To input another pair press <return>"
      LOCATE 19,5:PRINT"To see result, press <Esc>.":COLOR 7,0
      IF Q THEN LPRINT "To see result, press <Esc>."
2230  K$=INKEY$:IF K$="" GOTO 2230
      IF K$=CHR$(13) GOTO 2120
      IF K$=CHR$(27) THEN CLS:N=N-1:RETURN
      GOTO 2230
2270  CLS
      END
```

PROGRAM MISC9
INTERVAL VELOCITIES
FROM BOREHOLE SEISMIC SURVEY

Program MISC9 determines interval velocities from borehole seismic wave surveys. It can be used for both compressional and shear wave surveys with a constant or variable spacing of the geophone in the borehole. This program and the accompanying documentation are modified from Cummings (MGHCP, 1985).

Applications of this program to engineering geophysics include using interval velocities of both wave type to calculate elastic constants, using interval velocities in seismic stratigraphic interpretation, using a velocity column to develop characteristic site period, using interval velocities to identify hidden layers and blind zones in seismic refraction studies, using interval velocities for input to computer analysis for seismic design, using interval velocities to develop synthetic seismograms.

Figure 1 shows a diagram of the problem. Figure 2 shows the equations used in the program. An example problem, its solution, and the program listing follow.

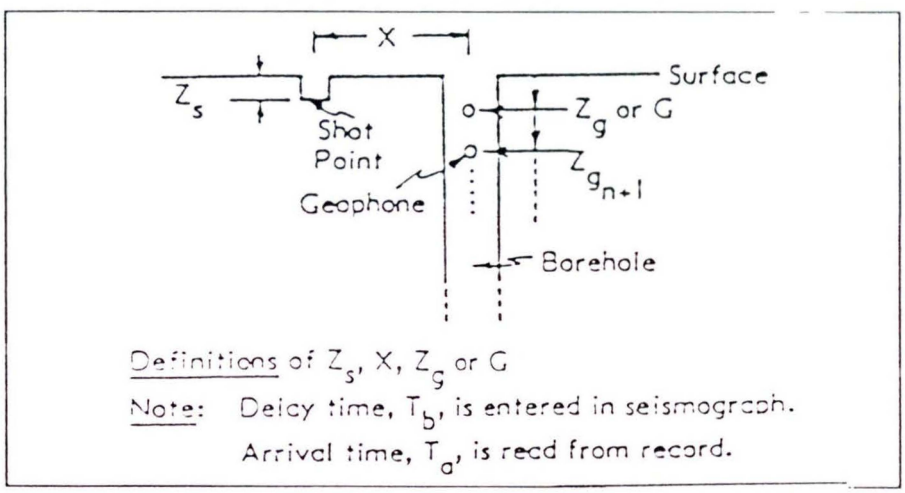


Figure 1. A borehole seismic survey. After Cummings (MGHCP, 1985).

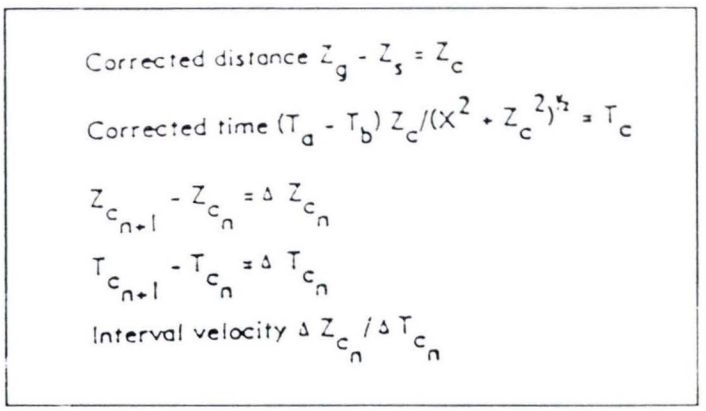


Figure 2. The equations used in program MISC9 to calculate interval velocities. After Cummings (MGHCP, 1985).

EXAMPLE 1. Determine the interval velocities for the following borehole survey. Geophones are at depths of 100, 200, 300, 400, and 500 ft. The corresponding arrival times were .005,.100,.150,.200,.250 s. The shot depth was 9 ft; the offset was 10 ft; the instrument delay was 0.004 s.

PROBLEM SOLUTION

```
SEG PROGRAM MISC9 INTERVAL VELOCITIES FROM BOREHOLE SEISMIC SURVEY
Depth to shot ? 9
Horizontal distance ? 10
Instrument delay time in s ? .004
# of geophone depths ? 5
Depth, time pair for geophone 1 ?
 100 , .005
Depth, time pair for geophone 2 ?
 200 , .1
Depth, time pair for geophone 3 ?
 300 , .15
Depth, time pair for geophone 4 ?
 400 , .2
Depth, time pair for geophone 5 ?
 500 , .25

DEPTH TO DEPTH TO  INTERVAL
 TOP     BOTTOM    VELOCITY
 100       200     1054.022
 200       300     1998.192
 300       400     1999.118
 400       500     1999.481
```

PROGRAM LISTING

```
' MISC9 INTERVAL VELOCITIES FROM BOREHOLE SEISMIC SURVEY
CLS
PRINT "SEG PROGRAM MISC9 INTERVAL VELOCITIES FROM BOREHOLE
 SEISMIC SURVEY"
'
' This program determines interval velocities from borehole
' seismic wave surveys.  It can be used for both compressional and
' shear wave surveys with a constant or variable spacing of the
' geophone in the borehole.  This program is a modification of an HP
' program by D.  Cummings.
'
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
IF Q THEN LPRINT "SEG PROGRAM MISC9 INTERVAL VELOCITIES FROM
 BOREHOLE SEISMIC SURVEY"
PRINT:INPUT "Depth to shot";ZS
IF Q THEN LPRINT:LPRINT "Depth to shot ? ";ZS
INPUT "Horizontal distance";X
IF Q THEN LPRINT "Horizontal distance ? ";X
INPUT "Delay time in s ";TB
IF Q THEN LPRINT "Instrument delay time in s ? ";TB
INPUT "# of geophone depths";N
IF Q THEN LPRINT "# of geophone depths ? ";N
FOR I=1 TO N:PRINT "Depth, time pair: geophone ";I;:INPUT ZG,TA
IF Q THEN LPRINT "Depth, time pair for geophone ";I;" ? ":LPRINT ZG","TA
ZC(I)=ZG-ZS 'Corrected distance
TC(I)=(TA-TB)*ZC(I)/(X^2+ZC(I)^2)^.5
NEXT I
FOR I=1 TO N-1
DZ=ZC(I+1)-ZC(I)
DT=TC(I+1)-TC(I)
VI(I)=DZ/DT
NEXT I
CLS
PRINT "DEPTH TO","DEPTH TO","INTERVAL"
IF Q THEN LPRINT "DEPTH TO","DEPTH TO","INTERVAL"
PRINT " TOP"," BOTTOM"," VELOCITY"
IF Q THEN LPRINT " TOP"," BOTTOM"," VELOCITY"
PRINT:IF Q THEN LPRINT
FOR I=1 TO N-1
PRINT ZC(I)+ZS,ZC(I+1)+ZS,VI(I)
IF Q THEN LPRINT ZC(I)+ZS,ZC(I+1)+ZS,VI(I)
NEXT I
END
```

PROGRAM RIP1
GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS

Program RIP1 calculates the geometric factor (in meters) for resistivity surveys using the Wenner, Schlumberger, dipole-dipole, rectangular bipole-dipole, or general arrays. This program is a modification of Campbell (MGHCP, 1981). The equations used are shown in Figures 1 and 2. Five example problems, their solutions, and the program listing follow.

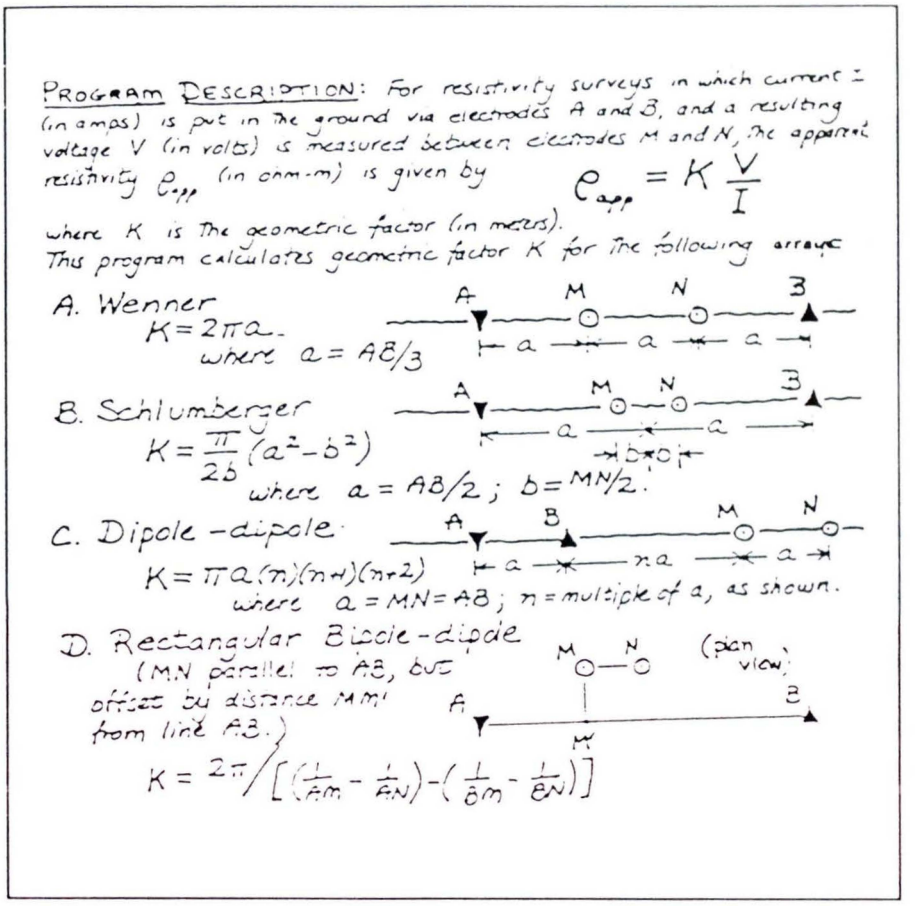


Figure 1. Equations used in program RIP1. After Campbell (MGHCP, 1981).

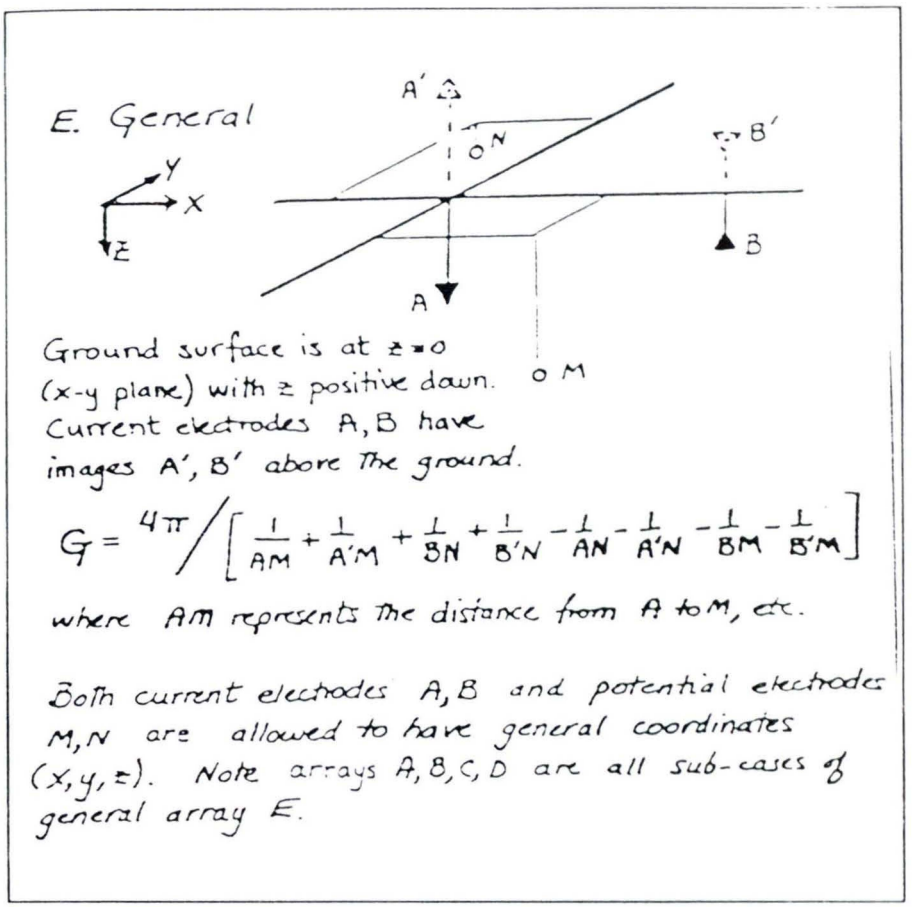


Figure 2. Equations used in program RIP1. After Campbell, 1981). Further information can be found in Zohdy et.al. (Applications of surface geophysics to ground-water investigations, 1974, Chapter D1 of Techniques of water resource investigations of the U.S. Geological Survey: US Government Printing Office, Washington,DC), and in Daniels (Three-dimensional resistivity and induced polarization modelling using buried electrodes, 1977, Geophysics, 42, 5, 1006-1019).

EXAMPLE 1. Construct a table of K factors for Schlumberger soundings with MN/2=20′, and AB/2=100′, 140′, 200′, 300′, 400′.

PROBLEM SOLUTION

```
SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS
Choose units for input:
ft <1> or m <2>? 1
Choose:
 Wenner Array     <1>
 Schlumberger Array <2>
 Dipole-dipole Array <3>
 Rect.  bipole-dipole <4>
 General array     <5>
# ? 2
Schlumberger Array
MN/2 ? 20
Number of readings for same MN/2 ? 5
Reading # 1 AB/2 ? 100
Geometric factor is 229.8165 m
Reading # 2 AB/2 ? 140
Geometric factor is 459.633 m
Reading # 3 AB/2 ? 200
Geometric factor is 947.9931 m
Reading # 4 AB/2 ? 300
Geometric factor is 2144.954 m
Reading # 5 AB/2 ? 400
Geometric factor is 3820.7 m
```

Example 2. Construct a table of K factors for Schlumberger soundings with MN/2=60′; AB/2=300′,400 ′, 600′, 800 ′, 1000′, 1400′.

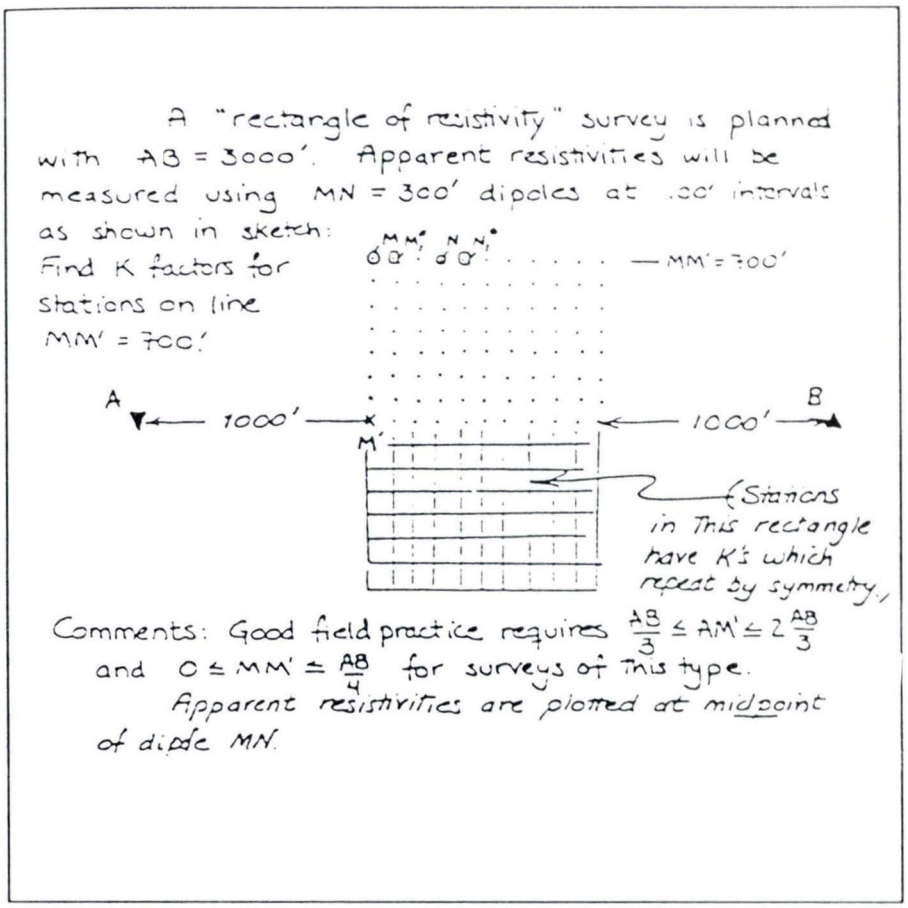
PROBLEM SOLUTION

```
SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS
Choose units for input:
ft <1> or m <2>? 1
Choose:
 Wenner Array     <1>
 Schlumberger Array <2>
 Dipole-dipole Array <3>
 Rect.  bipole-dipole <4>
 General array     <5>
# ? 2
Schlumberger Array
MN/2 ? 60
Number of readings for same MN/2 ? 6
Reading # 1 AB/2 ? 300
Geometric factor is 689.4496 m
Reading # 2 AB/2 ? 400
Geometric factor is 1248.032 m
Reading # 3 AB/2 ? 600
Geometric factor is 2843.98 m
Reading # 4 AB/2 ? 800
Geometric factor is 5078.307 m
```

```
Reading # 5 AB/2 ? 1000
Geometric factor is 7951.014 m
Reading # 6 AB/2 ? 1400
Geometric factor is 15611.57 m
```

EXAMPLE 3. Find K for a dipole-dipole survey with AB=MN=300′, for n=1, 2, 3.

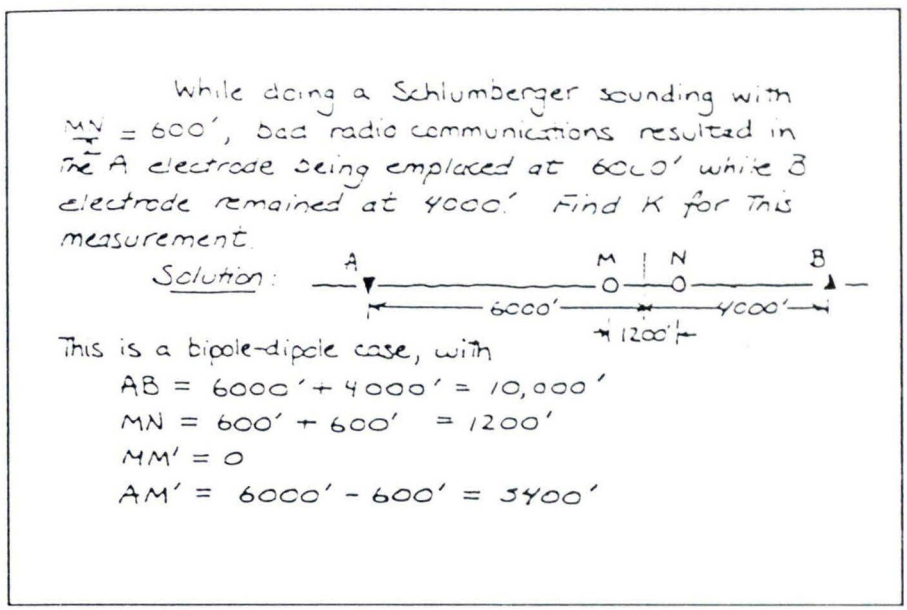
```
PROBLEM SOLUTION
SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS
Choose units for input:
ft <1> or m <2>? 1
Choose:
 Wenner Array     <1>
 Schlumberger Array <2>
 Dipole-dipole Array <3>
 Rect.  bipole-dipole <4>
 General array    <5>
# ? 3
Dipole-dipole array
AB ? 300
 N      Geometric factor
 1       1723.624 m
 2       6894.496 m
 3       17236.24 m
 4       34472.48 m
 5       60326.84 m
 6       96522.94 m
 7       144784.4 m
 8       206834.9 m
 9       284398 m
```



EXAMPLE 4. Calculate the K factors for the measurements described above. After Campbell (MGHCP, 1981).

```
PROBLEM SOLUTION
Choose units for input:
ft <1> or m <2>? 1
Choose:
 Wenner Array     <1>
 Schlumberger Array <2>
 Dipole-dipole Array <3>
 Rect.  bipole-dipole <4>
 General array    <5>
# ? 4
AB,MN,MM',AM' ? 3000, 300, 700, 1000
Delta AM' ? 100
# of readings ? 5
 AM'      Geometric Factor
 1000      8951.408 m
 1100      9259.727 m
```

```
1200        9479.102 m
1300        9593.054 m
1400        9593.057 m
```



EXAMPLE 5. Find K for the measurement described above. After Campbell (MGHCP, 1981).

```
PROBLEM SOLUTION
SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS
Choose units for input:
ft <1> or m <2>? 1
Choose:
 Wenner Array     <1>
 Schlumberger Array <2>
 Dipole-dipole Array <3>
 Rect.  bipole-dipole <4>
 General array    <5>
# ? 5
Point A: X,Y,Z coords ? 0, 0, 0
Point B: X,Y,Z coords ? 10000, 0, 0
Point M: X,Y,Z coords ? 5400, 0, 0
Point N: X,Y,Z coords ? 6600, 0, 0
Geometric factor is 17347.83
```

A mise-a-la-masse survey has electrode A implanted in massive sulfides encountered at 350 ft depth in a borehole and electrode B on the surface 5000 ft away. Potentials will be measured on the surface using a 100-foot dipole.
Take A = (0, 0, 350) B = (5000, 0, 0)
M = (0, 0, 0) N = (100, 0, 0)

EXAMPLE 6. Determine the K value for the measurement described above. After Campbell (MGHCP, 1981).

```
PROBLEM SOLUTION
SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS
Choose units for input:
ft <1> or m <2>? 1
Choose:
 Wenner Array     <1>
 Schlumberger Array <2>
 Dipole-dipole Array <3>
 Rect.  bipole-dipole <4>
 General array    <5>
# ? 5
Point A: X,Y,Z coords ? 0, 0, 350
Point B: X,Y,Z coords ? 5000, 0, 0
Point M: X,Y,Z coords ? 0, 0, 0
Point N: X,Y,Z coords ? 100, 0, 0
Geometric factor is 16797.52
```

PROGRAM LISTING

```
' RIP1  GEOMETRIC FACTORS FOR RESISTIVITY SURVEYS
CLS
PRINT "SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR
RESISTIVITY SURVEYS"
'
' This program calculates the geometric factor for resistivity surveys
' in which the current I (in amps) is put into the ground via electrodes
' A and B, and a resulting voltage V (in volts) is measured between
' electrodes M and N.  The apparent resistivity Pa = K V/I where K is the
' geometric factor (in m).  This program is a modification of HP programs
' by D.L.  Campbell and L.R.  Findhammer.
'
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
IF Q THEN LPRINT "SEG PROGRAM RIP1  GEOMETRIC FACTORS FOR
RESISTIVITY SURVEYS"
PRINT:IF Q THEN LPRINT
PRINT "Choose units for input:"
IF Q THEN LPRINT "Choose units for input:"
INPUT " ft <1> or m <2>";NA
```

```
      IF Q THEN LPRINT "ft <1> or m <2>? ";NA
      IF NA=1 THEN F$="FT" ELSE F$="m"
290   PRINT "Choose:"
      IF Q THEN LPRINT "Choose:"
      PRINT:IF Q THEN LPRINT
      PRINT " Wenner Array    <1>"
      IF Q THEN LPRINT " Wenner Array    <1>"
      PRINT " Schlumberger Array <2>"
      IF Q THEN LPRINT " Schlumberger Array <2>"
      PRINT " Dipole-dipole Array <3>"
      IF Q THEN LPRINT " Dipole-dipole Array <3>"
      PRINT " Rect.  bipole-dipole <4>"
      IF Q THEN LPRINT " Rect.  bipole-dipole <4>"
      PRINT " General array    <5>"
      IF Q THEN LPRINT " General array    <5>"
      PRINT
      IF Q THEN LPRINT
      INPUT "# ";NA
      IF Q THEN LPRINT "# ? ";NA
      IF NA<>1 AND NA<>2 AND NA<>3 AND NA<>4 AND NA<>5 THEN 290
      IF NA=1 THEN 520
      IF NA=2 THEN 660
      IF NA=3 THEN 830
      IF NA=4 THEN 970
      IF NA=5 THEN 1200
520   'Wenner
      PRINT "Wenner Array"
      IF Q THEN LPRINT "Wenner Array"
      INPUT "# of readings";N
      IF Q THEN LPRINT "# of readings ? ";N
      FOR I=1 TO N
      PRINT "Reading #";I;:INPUT "A-spacing ";A
      IF Q THEN LPRINT "Reading #";I;:LPRINT "A-spacing ? ";A
      IF F$="FT" THEN A=A/3.2808
      K=2*3.141592*A
      PRINT "Geometric factor is ";K;"m"
      IF Q THEN LPRINT "Geometric factor is ";K;"m"
      NEXT
      END
660   'Schlumberger Array
      PRINT "Schlumberger Array"
      IF Q THEN LPRINT "Schlumberger Array"
      INPUT "MN/2 ";B
      IF Q THEN LPRINT "MN/2 ? ";B
      IF F$="FT" THEN B=B/3.2808
      INPUT "Number of readings for same MN/2";N
      IF Q THEN LPRINT "Number of readings for same MN/2 ? ";N
      FOR I=1 TO N
      PRINT "Reading #";I;:INPUT "AB/2 ";A
      IF Q THEN LPRINT "Reading #";I;:LPRINT "AB/2 ? ";A
      IF F$="FT" THEN A=A/3.2808
      K=3.141592*(A^2-B^2)/(2*B)
      PRINT "Geometric factor is ";K;"m"
      IF Q THEN LPRINT "Geometric factor is ";K;"m"
      NEXT
      END
830   'Dipole-dipole array
      PRINT "Dipole-dipole array"
      IF Q THEN LPRINT "Dipole-dipole array"
      INPUT "AB ";A
      IF Q THEN LPRINT "AB ? ";A
      IF F$="FT" THEN A=A/3.2808
      PRINT " N   ","Geometric factor"
      IF Q THEN LPRINT " N   ","Geometric factor"
      FOR I=1 TO 9
      K=3.141592*A*I*(I+1)*(I+2)
      PRINT I,K;"m"
      IF Q THEN LPRINT I,K;"m"
      NEXT
```

```
END
970 'Rectangular bipole-dipole array.
INPUT "AB,MN,MM',AM'";AB,MN,MMP,AMP
IF Q THEN LPRINT "AB,MN,MM',AM' ? ";AB,MN,MMP,AMP
IF F$="FT" THEN                                AB=AB*.3048:MN=MN*.3048:MMP=MMP*.3048:AMP=AMP*.3048
INPUT "Delta AM'";D
IF Q THEN LPRINT "Delta AM' ? ";D
IF F$="FT" THEN D=D*.3048
INPUT "# of readings";N
IF Q THEN LPRINT "# of readings ? ";N
PRINT:PRINT " AM'","Geometric Factor"
IF Q THEN LPRINT:LPRINT " AM'","Geometric Factor"
FOR I=1 TO N
AM=SQR(AMP^2+MMP^2)
AN=SQR((AMP+MN)^2+MMP^2)
BM=SQR(MMP^2+(AB-AMP)^2)
BN=SQR(MMP^2+(AB-AMP-MN)^2)
K=2*3.141592/((1/AM-1/AN)-(1/BM-1/BN))
IF F$="FT" THEN FAC=1/.3048 ELSE FAC=1
PRINT AMP*FAC,K;"m"
IF Q THEN LPRINT AMP*FAC,K;"m"
AMP=AMP+D
NEXT
END
1200 ' General array
PRINT:IF Q THEN LPRINT
INPUT "Point A: X,Y,Z coords ";AX,AY,AZ
IF Q THEN LPRINT "Point A: X,Y,Z coords ? ";AX,AY,AZ
INPUT "Point B: X,Y,Z coords ";BX,BY,BZ
IF Q THEN LPRINT "Point B: X,Y,Z coords ? ";BX,BY,BZ
INPUT "Point M: X,Y,Z coords ";MX,MY,MZ
IF Q THEN LPRINT "Point M: X,Y,Z coords ? ";MX,MY,MZ
INPUT "Point N: X,Y,Z coords ";NX,NY,NZ
IF Q THEN LPRINT "Point N: X,Y,Z coords ? ";NX,NY,NZ
AM=SQR((AX-MX)^2+(AY-MY)^2+(AZ-MZ)^2)
APM=SQR((AX-MX)^2+(AY-MY)^2+(-AZ-MZ)^2)
BN=SQR((BX-NX)^2+(BY-NY)^2+(BZ-NZ)^2)
BPN=SQR((BX-NX)^2+(BY-NY)^2+(-BZ-NZ)^2)
AN=SQR((AX-NX)^2+(AY-NY)^2+(AZ-NZ)^2)
APN=SQR((AX-NX)^2+(AY-NY)^2+(-AZ-NZ)^2)
BM=SQR((BX-MX)^2+(BY-MY)^2+(BZ-MZ)^2)
BPM=SQR((BX-MX)^2+(BY-MY)^2+(-BZ-MZ)^2)
K=4*3.141592/(1/AM+1/APM+1/BN+1/BPN-1/AN-1/APN-1/BM-1/BPM)
IF F$="FT" THEN K=K/3.2808
PRINT "Geometric factor is ";K
IF Q THEN LPRINT "Geometric factor is ";K
END
```

PROGRAM RIP4
THEORETICAL WENNER AND SCHLUMBERGER
VERTICAL ELECTRICAL SOUNDINGS

This program computes theoretical vertical electrical sounding curves for the Schlumberger and Wenner electrode arrays. The earth structure must be a horizontally layered medium consisting of up to nine layers over a halfspace. The input consists of layer thicknesses, resistivities, and array geometry. The output consists of electrode spacing-apparent resistivity pairs sampled at six points per decade of electrode spacing. For the Schlumberger array, the electrode spacing is AB/2; for the Wenner array, it is AB/3, where AB is the distance between outside current electrodes. The user input the minimum and maximum electrode spacings to be calculated. The units used are m and ohm-m. This program and documentation are modified from Zhody and Campbell (MGHCP, 1981) and Haines and Campbell (MGHCP, 1981).

The convolution method is used with Ghosh's filters to compute sounding curves. The equations are shown in Figure 1. For each electrode spacing, the computations involve two steps. First, the kernel function B(x) is calculated from the layer thicknesses and resistivities at nine (Schlumberger) or ten (Wenner) abscissa values (x). These abscissa values depend on the particular value of the electrode spacing which are equally spaced at six points per log cycle. Each electrode spacing used is multiplied by Ghosh's shift factor of 1.05 for Schlumberger or 1.36 for Wenner spacings. Second B(x) is convolved with the appropriate Ghosh filter coefficients to compute the apparent resistivity at each electrode spacing.

This program calculates resistivities at six points per log cycle but only uses three points per cycle in the calculation. Hence, it may prove

inadequate for computing sounding curve branches that steeply descend. Be wary of this program's results whenever a conducting layer has a resistivity less than 5 percent of the overlying material. An example problem, its solution, and the program listing follow.

First, the input layered structure is used to calculate a digital kernel function $B(x)$, where x is related to the present spacing a. Second, $B(x)$ is convolved with a set of coefficients (Ghosh, 1971), which are specific to the array in use, to find $\rho_{app}(a)$. Iteration is accomplished by incrementing a, hence x, by 1/3 of a log cycle; B(that x) becomes $B(x-\Delta x)$; all other $B(x)$ are cascaded in memory so that $B(x-j\Delta x)$ occupies $B(x-(j-1)\Delta x)$ slot; convolution is again performed; and so on.

EQUATIONS: $\Delta x = 10^{1/3}$

Wenner	$f = 1.36$	$x = a/10^{8/3}$
Schlumberger	$f = 1.05$	$x = a/100$

1. To get $B(x)$ = kernel function

   a. Initialize for bottom layer (half-space)

   $B_i = 1$ $\qquad R_i = \rho_n$

   b. Iterate upward through all layers i

   $R_i = B_i \cdot R_i$

   $K_i = (\rho_{i-1} - R_i)/(\rho_{i-1} + R_i)$

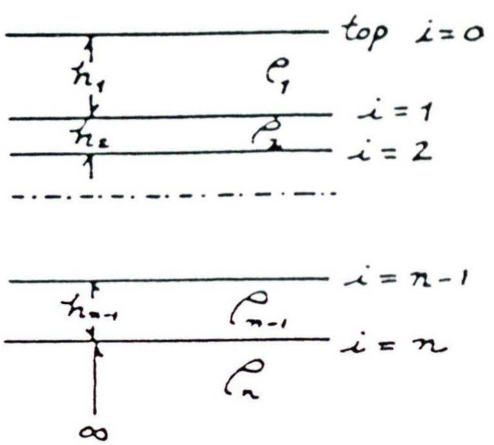
   $\alpha_i = (-2h_{i-1})/(f \cdot x)$

   $Q_i = K_i \cdot \exp(\alpha_i)$

   $B_{i-1} = (1 - Q_i)/(1 + Q_i)$

   c. After iterating through all layers

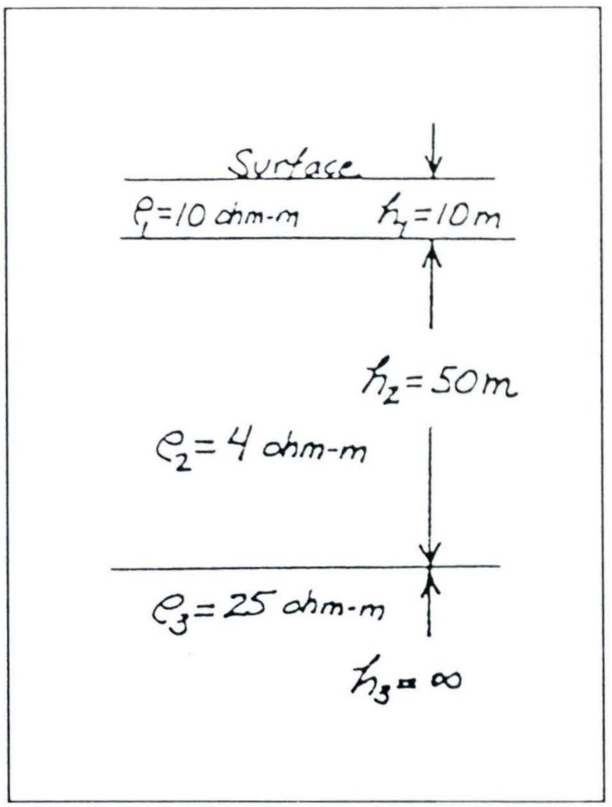
   $B(x) = B_1 \cdot \rho_1$



c. Convolve with Ghosh coefficients, G_j

$$\rho_{app}(a) = \sum_{j=0}^{9} G_j \cdot B(x - j\Delta x)$$

Figure 1. Equations used in program RIP4. After Zhody and Campbell (MGHCP, 1981).



EXAMPLE 1. Compute theoretical soundings for the above model using both the Wenner and Schlumberger arrays.

PROBLEM SOLUTION

```
SEG PROGRAM RIP4 VES: WENNER/SCHLUMBERGER
Choose:  Schlumberger <S> or Wenner <W> Sounding ?  S
Number of layers including halfspace ? 3
Layer 1
Resistivity in ohm-m, thickness in m ? 10 , 10
Layer 2
Resistivity in ohm-m, thickness in m ? 4 , 50
Layer 3
Resistivity in ohm-m, thickness in m ? 25 , 0

Min electrode spacing, max electrode spacing in m ? 1 , 1000
```

<See next page for results.>

```
  SPACING (m)   Pa (ohm-m)
    1.00        9.98
    1.47        9.98
    2.15        9.98
    3.17        9.97
    4.64        9.91
    6.82        9.74
   10.00        9.32
   14.70        8.40
   21.54        7.05
   31.67        5.76
   46.42        5.09
   68.23        5.29
  100.00        6.35
  147.00        8.16
  215.44       10.50
  316.70       13.19
  464.16       15.96
  682.31       18.59
 1000.00       20.81

SEG PROGRAM RIP4 VES: WENNER/SCHLUMBERGER
Choose: Schlumberger <S> or Wenner <W> sounding ? W
Number of layers including halfspace ? 3
Layer 1
Resistivity in ohm-m, thickness in m ? 10 , 10
Layer 2
Resistivity in ohm-m, thickness in m ? 4 , 50
Layer 3 Resistivity in ohm-m, thickness in m ? 25 , 0
Min electrode spacing, max electrode spacing in m ? 1 , 1000

  SPACING (m)   Pa (ohm-m)
    1.00        9.99
    1.47        9.98
    2.15        9.97
    3.17        9.92
    4.64        9.76
    6.82        9.35
   10.00        8.52
   14.70        7.27
   21.54        5.98
   31.67        5.18
   46.42        5.21
   68.23        6.09
  100.00        7.73
  147.00        9.97
  215.44       12.58
  316.70       15.34
  464.16       17.98
  682.31       20.30
 1000.00       22.08
```

PROGRAM LISTING

```
      ' RIP4  VES: WENNER/SCHLUMBERGER
      CLS:PRINT "SEG PROGRAM RIP4 VES: WENNER/SCHLUMBERGER
      ' Given an input resistivity structure of up to 10 layers including
      ' a halfspace, this program calculates the theoretical Wenner or
      ' Schlumberger vertical electric sounding, VES, which would be
      ' seen over the layered structure.  Output consists of array
      ' spacing--apparent resistivity pairs.  The array spacing is
      ' AB/2 for the Schlumberger array and AB/3 for the Wenner where
      ' AB is the distance between the outer current electrodes.  The
      ' apparent resistivity is sampled at 6 points per decade.  This
      ' program is a translation of a TI program by D.H.  Haines and
      ' D.L.  Campbell.
      PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
      IF Q THEN LPRINT "SEG PROGRAM RIP4 VES: WENNER/SCHLUMBERGER
      PRINT:IF Q THEN LPRINT
      DIM S(100),XX(50),RHO(50):DEF FNSQ(X)=X*X
      DEF FNSN(X)=SIN(.01745*X):DEF FNCS(X)=COS(.01745*X)
      DEF FNTN(X)=TAN(.01745*X)
      GOTO 990 'Data Entry
320   'Store resistivity--thickness pairs
      DA=D:S(S( 8))=DA:S( 8 )=S( 8 )-1 :DB=T:T=DA:S(S( 8))=DB:DC=T:T=DB
      S( 8 )=S( 8 )-1:S( 7 )=S( 7 )+1:T=0: D=DC
      RETURN
360   'Main Calculation
      DC=D : DD=(S( 7)):S( 29)=DD  '# of layers
      D=DD
400   '
      DD=D : S( 7 )=S( 7 )-1:DE=(1):S( 32)=DE 'Initialize Bi register
      S( 8 )=S( 8 )+1 : D=DE
440   'Begin loop for kernel calculation
      DE=D: DF=((S(S( 8)))*(S( 32))): S( 32)=DF
      DG=(2): S( 8)=S( 8)+DG
      DH=(((S(S( 8)))-(S( 32)))/((S(S( 8)))+(S( 32))))
      S( 32)=DH: S( 8 )=S( 8 )+1
      DI=((-(2))*(S(S( 8)))/(S( 30))/(S( 31)))
      DI=EXP(DI): DI=DI*S(32): S( 32)=DI: DJ=DI
      DK=(((-(DJ))+(1))/((1)+(S( 32))))
      S( 32)=DK : S( 8 )=S( 8 )-1
      S( 7 )=S( 7 )-1:IF S( 7 )<>0 THEN GOTO 440
      DL=(S(S( 8))): S( 32)=S( 32)*DL
      DM=(S( 32)): D=DM
      GOSUB 700
      DM=D :IF F( 2 )=0 THEN GOTO 650
      IK=IK+2:XX(IK)=DM:DN=T:T=DM
      RHO(IK)=DN  'Apparent resistivity result
      DO=S( 53 ):S( 53 )=DN : D=DO: IF DO>=T THEN GOTO 630
      DO=D: DP=S( 53 ):S( 53 )=DO: D=DP
      RETURN
630   '
      DP=D : DQ=S( 53 ):S( 53 )=DP : D=DQ
650   '
      DQ=D :DR=((10^(1!/(3)))*(S( 30))):S( 30)=DR: D=DR
670   'Initialize loop and index registers
      DR=D:DS=(S( 29)):S( 7)=DS: DT=((DS)*(2)-(1)):S( 8)=S( 8)-DT: D=DT
      GOTO 400
700   'Enter new Bi and convolve
      DT=D:DU=T:T=DT:IF F( 2 )=0 THEN GOTO 770
      S( 2 )=S( 2 )-1: DV=(S( 0)):S( 6)=DV: S( 0 )=S( 0 )+1: D=DV
730   'Cascade kernel elements Bi in memory
      DV=D:DW=(S(S( 0))):S(S( 6))=DW:S( 0 )=S( 0 )+1: S( 6 )=S( 6 )+1
      S( 2 )=S( 2 )-1:IF S( 2 )<>0 THEN GOTO 730
      DX=(S( 3)):S( 2)=DX : S( 0 )=S( 0 )-1 : D=DX
770   'Store newest Bi--check if enough others to convolve
      DX=D: DY=T:T=DX : S(S( 0))=DY: S( 4 )=S( 4 )+1
      IF F( 1 )=1 THEN GOTO 850
      S( 0 )=S( 0 )+1 : S( 4 )=S( 4 )+1: T=(S( 2)): DZ=(S( 4)): D=DZ
      IF DZ=T THEN GOTO 960
```

```
DZ=D:S( 4 )=S( 4 )-1 :DA=(S( 4)):D=DA
RETURN
D=DA
850  'Convolve
DB=((S(S( 1)))*(S(S( 0))))
S( 5)=S( 5)+DB
S( 1 )=S( 1 )+1
S( 0 )=S( 0 )-1
S( 2 )=S( 2 )-1:IF S( 2 )<>0 THEN GOTO 850
S( 0 )=S( 0 )+1
DC=(S( 3)):S( 2)=DC:DD=(-(DC)):S( 1)=S( 1)+DD
F( 2 )=1:DE=(-(S( 5))):S( 5)=S( 5)+DE : T=(-(DE))
DF=((S( 30))/(S( 55))): D=DF
RETURN
960  'Set flags
DF=D : F( 1 )=1:S( 4 )=S( 4 )-1: T=0 : D=DF
RETURN
990  ' DATA ENTRY
1000 INPUT "Choose: Schlumberger <S> or Wenner <W> sounding";A$
IF A$<>"S" AND A$<>"W" THEN 1000
IF Q THEN LPRINT "Choose: Schlumberger <S> or Wenner <W> sounding          ?";A$
IF A$="W" THEN 1040 ELSE 1080
1040 S(9)=.0284:S(10)=.4582:S(11)=1.5662:S(12)=-1.3341:S(13)=.3473
                S(14)=-9.350001E-02:S(15)=.04016:S(16)=-.0253:S(17)=.0179:S(18)=-.0067
S(55)=10:S(54)=10^(8/3):S(31)=1.36
GOTO 1120
1080 'Ghosh coefficients for Schlumberger array
S(9)=.0225:S(10)=-.0499:S(11)=.1064:S(12)=.1854:S(13)=1.972
S(14)=-1.5716:S(15)=.4018:S(16)=-.0814:S(17)=.0148:S(18)=0
S(55)=10:S(54)=100:S(31)=1.05
1120 '
S(0)=19:S(1)=9:S(2)=10:S(3)=10:F(4)=1:S(8)=52
1140 INPUT "Number of layers including halfspace";NL
IF Q THEN LPRINT "Number of layers including halfspace ? ";NL
IF NL>10 THEN PRINT "Max # allowed is 10":GOTO 1140
FOR I= 1 TO NL
PRINT "Layer";I:INPUT "Resistivity in ohm-m, thickness in m";T,D
IF Q THEN LPRINT "Layer";I:LPRINT "Resistivity in ohm-m, thickness in
 m ? ";T","D
GOSUB 320
NEXT
PRINT :IF Q THEN LPRINT
INPUT "Min electrode spacing, max electrode spacing in m";AMIN,AMAX
IF Q THEN LPRINT "Min electrode spacing, max electrode spacing in m ?
 ";AMIN","AMAX
PRINT:PRINT"<<WAIT--CALCULATION IN PROGRESS>>" :IF Q THEN LPRINT
S(53)=AMAX:S(30)=AMIN/S(54):IK=-1
GOSUB 360 'Main calculation
S(0)=19:S(1)=9:S(2)=10:S(3)=10:F(4)=1:F(1)=0:S(4)=0:S(5)=0:S(6)=0
AMIN=AMIN*1.47:S(30)=AMIN/S(54):F(2)=0:F(3)=0:IKM=IK:IK=0
GOSUB 670 'Do it again
PRINT "   SPACING (m)  Pa (ohm-m)":PRINT
IF Q THEN LPRINT "   SPACING (m)  Pa (ohm-m)":LPRINT
IF A$="W" THEN IKM=IKM-4
FOR IK=1 TO IKM
IF A$="S" THEN PRINT USING "############.##";XX(IK),RHO(IK)
IF A$="S" AND Q THEN LPRINT USING "############.##";XX(IK),RHO(IK)
IF A$="W" THEN PRINT USING "############.##";XX(IK+4),RHO(IK)
IF A$="W" AND Q THEN LPRINT USING
 "############.##";XX(IK+4),RHO(IK)
NEXT
END
```

PROGRAM RIP5
SP PATCH MODELS

This program computes the self-potential (SP) anomaly due to a rectangular source along a vertical contact. The potential is computed on the surface of a halfspace at equally spaced stations along a line specified by the user. The model source voltage is produced by differences in electrokinetic coupling coefficients such as the streaming potential. This program is useful for interpretation of SP data measured near vertical contacts. This program and documentation are modified from Fitterman (MGHCP, 1981).

The equations used are shown in Figure 1 along with the geometry. For a discussion including a complete derivation, see Fitterman (Calculation of self-potential anomalies near vertical contacts, 1979, Geophysics, 44, 195-205).

The program features a menu which allows input of parameters in any order. The location of the profile is specified by the coordinates of the first and last stations. Any station increment can be specified. The profile can be oriented at any azimuth relative to the strike of the model. An example problem, its solution, and the program listing follow.

EQUATIONS

The geometry of the problem is given in Figure 1. The anomaly is given by

$$V(x,y,o) = \frac{S_o}{\pi(1 + \sigma_1/\sigma_2)} \{f(x,y;t/2,b) - f(x,y;t/2,a) - f(x,y;-t/2,b) + f(x,y;-t/2,a)\} \quad (1)$$

where

$$f(x,y;\alpha,\beta) = \tan^{-1} \frac{(x + \alpha)\beta}{y\{(x + \alpha)^2 + y^2 + \beta^2\}^{1/2}} \quad (2)$$

When $y > o$ the upper subscripts are used, while for $y < o$ the lower subscripts are used.

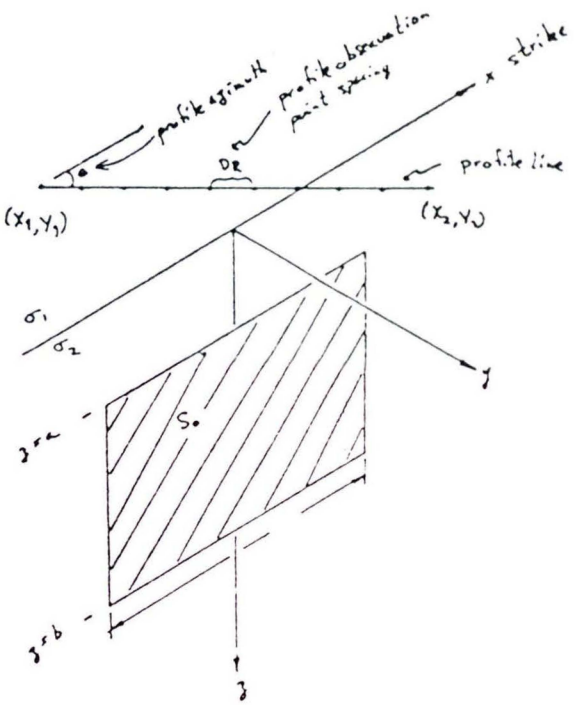


Figure 1. The geometry and equations used in program RIP5. After Fitterman (MGHCP, 1981).

EXAMPLE 1. Compute the self-potential for a model with the following parameters. The depth to the top of the source is 0.25 km, the depth to the base is 3.75 km, the source half-length is 0.75 km, the source intensity is 100 mv, and the conductivity ratio is 3. Start the profile at (-1.5 km, -1.0 km). Stop the profile at (0.5 km, 0.5 km). Use a station increment of 0.5 km. After Fitterman (MGHCP, 1981).

PROBLEM SOLUTION

SEG PROGRAM RIP5 SP PATCH MODELS

0 Depth to top of Source	0.25	X	Y	V
1 Depth to bottom of source	3.75	-1.500	-1.000	-9.221
		-1.100	-0.700	-12.948
2 Source half length	0.75	-0.700	-0.400	-19.182
		-0.300	-0.100	-12.150
3 Source intensity	100.0	0.100	0.200	7.126
		0.500	0.500	7.947
4 Conductivity ratio	3.00			
5 Starting X coordinate	-1.50			
6 Starting Y coordinate	-1.00			
7 Ending X coordinate	0.50			
8 Ending Y coordinate	0.50			
9 Spacing Distance	0.50			

PROGRAM LISTING

```
' SP PATCH MODELS
' This program computes vertical contact patch models.  It is
' modified from
' a hand-calculator program by D.V.  Fitterman.
TITLE$="SEG PROGRAM RIP5     SP PATCH MODELS"
PRINT TITLE$:IF Q THEN LPRINT TITLE$
PRINT:INPUT "Hardcopy <Y/N>";A$:IF A$="Y" OR A$="y" THEN Q=1
IF Q THEN LPRINT TITLE$
PRINT:IF Q THEN LPRINT
PRINT:IF Q THEN LPRINT
CLS:LOCATE 5,30:COLOR 0,7:PRINT " RIP-5 ":COLOR 7,0
LOCATE 7,10:PRINT "Computation of Vertical Contact Self-Potential"
LOCATE 8,10:PRINT "Based on calculator program by David Fitterman"
LOCATE 9,10:PRINT "BASIC program by Doug Dodge"
LOCATE 12,10:PRINT "Program calculates self -potential at stations  along an"
LOCATE 13,10:PRINT "arbitrary straight line path.Parameters may be adjusted"
LOCATE 14,10:PRINT "at any time and potential easily recalculated."
LOCATE 20,20:COLOR 15,0:PRINT "To continue press any key ":COLOR 7,0
300  K$=INKEY$:IF K$="" GOTO 300
     CLS:PI=4*ATN(1)
     LOCATE 2,2:PRINT "0 Depth to top of Source":LOCATE 2,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 4,2:PRINT "1 Depth to bottom of source":LOCATE 4,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 6,2:PRINT "2 Source half length":LOCATE 6,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 8,2:PRINT "3 Source intensity":LOCATE 8,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 10,2:PRINT "4 Conductivity ratio":LOCATE 10,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 12,2:PRINT "5 Starting X coordinate":LOCATE 12,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 14,2:PRINT "6 Starting Y coordinate":LOCATE 14,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 16,2:PRINT "7 Ending X coordinate":LOCATE 16,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 18,2:PRINT "8 Ending Y coordinate":LOCATE 18,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
     LOCATE 20,2:PRINT "9 Spacing Distance":LOCATE 20,30:COLOR 0,7
     PRINT SPACE$(7):COLOR 7,0
430  LOCATE 10,39:PRINT "To enter or change a parameter just"
     LOCATE 11,39:PRINT "press the number in front of it"
     LOCATE 13,39:PRINT "To Calculate SP anomaly along traverse"
     LOCATE 14,39:PRINT "just press <return>"
     LOCATE 16,39:PRINT "To return to system press <Esc> "
     '----------choose a parameter to enter
490  K$=INKEY$:IF K$="" GOTO 490
     IF K$="0" THEN GOSUB 1180:GOTO 430
     IF K$="1" THEN GOSUB 1280:GOTO 430
     IF K$="2" THEN GOSUB 1340:GOTO 430
     IF K$="3" THEN GOSUB 1420:GOTO 430
     IF K$="4" THEN GOSUB 1480:GOTO 430
     IF K$="5" THEN GOSUB 1560:GOTO 430
     IF K$="6" THEN GOSUB 1630:GOTO 430
     IF K$="7" THEN GOSUB 1700:GOTO 430
     IF K$="8" THEN GOSUB 1770:GOTO 430
     IF K$="9" THEN GOSUB 1840:GOTO 430
     IF K$=CHR$(13) THEN GOSUB 640:GOTO 430:'calculate potentials
     IF K$=CHR$(27) THEN CLS:END
     GOTO 490
     '
640  'sub to calculate surface potential
     IF B<=0! OR L2<=0! OR SIG12<=0! OR DR<=0! THEN RETURN
     GOSUB 1900:'erase the right half of screen
     LOCATE 2,38:PRINT "    X         Y         V"
     R2=SQR((X2-X1)^2+(Y2-Y1)^2)
     IF X1-X2=0 THEN THETA=PI/2:GOTO 710
```

```
      THETA=ATN((Y2-Y1)/(X2-X1))
710   N=INT(R2/DR)+1
      K=3
      FOR J=1 TO N
      K=K+1
      RC=(J-1)*DR
      XC=X1+RC*COS(THETA):YC=Y1+RC*SIN(THETA)
      GOSUB 1000: 'get the potential
      FORM$="###.###    ###.###    ###.###"
      LOCATE K,38:PRINT USING FORM$;XC,YC,SI
      IF K>19 THEN GOSUB 920:' output will not fit on page.  start a new one
      NEXT
      IF Q THEN GOSUB 1940
      LOCATE K+2,39:COLOR 15,0:PRINT "To continue press any key":COLOR 7,0
840   K$=INKEY$:IF K$="" GOTO 840
      GOSUB 1900
      RETURN
      '*****************************************************
      '
      ' The following sub lets user look at first 20 lines of output and
      ' prompts for a keystroke to display more information
      IF Q THEN GOSUB 1940
920   IF Q THEN GOSUB 1940
      LOCATE K+2,38:PRINT "To continue press any key"
940   K$=INKEY$:IF K$="" GOTO 940
      GOSUB 1900:K=3
      LOCATE 2,38:PRINT "    X          Y          V"
      RETURN
      '*****************************************************
      '
1000  'subroutine to get si(x,y,0)
      ALPH=L2:BET=B:GOSUB 1100:F1=V
      BET=A:GOSUB 1100:F2=V
      ALPH=-ALPH:GOSUB 1100:F4=V
      BET=B:GOSUB 1100:F3=V
      SI=S0/PI/(1+SIG12)*(F1-F2-F3+F4)
      IF YC<0 THEN SI=SI*SIG12
      RETURN
      '*************************************************************
      '
1100  'subroutine to get f(x,y;α,ß)
      NUM=(ALPH+XC)*BET
      DEN=YC*SQR((XC+ALPH)^2+YC^2+BET^2)
      IF DEN=0! THEN DEN=1!
      V=ATN(NUM/DEN)
      '*****************************************************
      RETURN
      '
1180  ' sub to input depth to top of source
      '
      LOCATE 22,20:INPUT "input depth to top of source in kilometers ",A
      FORM1$="###.##"
      LOCATE 2,31:COLOR 0,7:PRINT USING FORM1$;A:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60)
      RETURN
      '*****************************************
      'sub to input depth to bottom of source
1280  '
      LOCATE 22,20:INPUT "input depth to bottom of source in kilometers ",B
      FORM$="###.##"
      LOCATE 4,31:COLOR 0,7:PRINT USING FORM$;B:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '*********************************
1340  '
      'sub to input source half length
      LOCATE 22,20:INPUT "input source half length in kilometers ",L2
      FORM$="###.##"
      LOCATE 6,31:COLOR 0,7:PRINT USING FORM$;L2:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
```

```
      '************************************
1420  'sub to get source intensity
      LOCATE 22,20:INPUT "input source intensity in millivolts ",S0
      FORM$="###.#"
      LOCATE 8,31:COLOR 0,7:PRINT USING FORM$;S0:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
1480  '
      'sub to input conductivity ratio
      LOCATE 22,20:INPUT "input conductivity ratio σ1/σ2 ",SIG12
      FORM$="###.##"
      LOCATE 10,31:COLOR 0,7:PRINT USING FORM$;SIG12:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
1560  'sub to input x coordinate of start
      LOCATE 22,20:INPUT "input x coordinate of profile starting point ",X1
      FORM$="###.##"
      LOCATE 12,31:COLOR 0,7:PRINT USING FORM$;X1:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
1630  'sub to input y coordinate of start
      LOCATE 22,20:INPUT "input y coordinate of profile starting point ",Y1
      FORM$="###.##"
      LOCATE 14,31:COLOR 0,7:PRINT USING FORM$;Y1:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
1700  'sub to get x coordinate of ending point
      LOCATE 22,20:INPUT "input x coordinate of profile ending point ",X2
      FORM$="###.##"
      LOCATE 16,31:COLOR 0,7:PRINT USING FORM$;X2:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
1770  'sub to get y coordinate of ending point
      LOCATE 22,20:INPUT "input y coordinate of profile ending point ",Y2
      FORM$="###.##"
      LOCATE 18,31:COLOR 0,7:PRINT USING FORM$;Y2:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
      '
1840  'sub to input station spacing
      LOCATE 22,20:INPUT "input observation point spacing in kilometers ",DR
      FORM$="###.##"
      LOCATE 20,31:COLOR 0,7:PRINT USING FORM$;DR:COLOR 7,0
      LOCATE 22,20:PRINT SPACE$(60):RETURN
      '****************************************
1900  'sub to erase right hand side of screen
      FOR M=1 TO 22
      LOCATE M,38:PRINT SPACE$(41):NEXT
      RETURN
1940  ' PRINTSCREEN
      FOR ROW=1 TO 24
      FOR COL=1 TO 78
      LPRINT CHR$(SCREEN(ROW,COL));
      NEXT COL
      LPRINT CHR$(SCREEN(ROW,79))
      NEXT ROW
      RETURN:END
```

PROGRAM SEIS12
TRAVEL TIMES FOR LAYERED MEDIA

This program computes the reflection time T at shot-receiver distance X for a given set of layer parameters. The user enters the velocity and thickness of each layer above a halfspace, the number of wave traverses in each layer, and the shot-receiver distance. The program uses an iterative procedure in conjunction with Snell's law to find the correct ray path. The net travel time is then calculated. This program is based on a calculator program by Wiggins (MGHCP, 1981). An example problem, its solution, and the program listing follow.

EXAMPLE 1. Find the travel time for the primary reflection for a two layer over a halfspace model with the following parameters. V1=1000 ft/s; H1=1000 ft; V2=1000 ft; V2=2000 ft/s. Use shot-receiver distances of 0, 1000 ft, and 2000 ft. Repeat the above model with a multiple reflection in layer 1.

```
PROBLEM SOLUTION
Number of layers in model? <Must be from 2 to 10>        3

Thickness of  Layer  1 in feet?  1000
Velocity of   Layer  1 in ft/s ?  1000
Input number of traverses of Layer  1 ?  2
Thickness of  Layer  2 in feet?  1000
Velocity of   Layer  2 in ft/s ?  2000
Input number of traverses of Layer  2 ?  2
Distance to receiver ?  0
The value of T is  3.0000 seconds

To try another x press 1
To input another model press 2
To quit program press <esc>
1
Distance to receiver ?  1000
The value of T is  3.0816 seconds

To try another x press 1
To input another model press 2
To quit program press <esc>
1
Distance to receiver ?  2000
The value of T is  3.3089 seconds
```

```
<Repeat the above model with a multiple reflection in layer 1.>

To try another x press 1
To input another model press 2
To quit program press <esc>
2
Number of layers in model? <Must be from 2 to 10>        3

Thickness of  Layer  1 in feet?  1000
Velocity of   Layer  1 in ft/s ?  1000
Input number of traverses of              Layer  1 ?  4
Thickness of  Layer  2       in feet?  1000
Velocity of   Layer  2       in ft/s ?  2000
Input number of traverses of              Layer  2 ?  2
Distance to receiver ?  0
The value of T is  5.0000 seconds

To try another x press 1
To input another model press 2
To quit program press <esc>
1
Distance to receiver ?  1000
The value of T is  5.0619 seconds

To try another x press 1
To input another model press 2
To quit program press <esc>
1
Distance to receiver ?  2000
The value of T is  5.2406 seconds

To try another x press 1
To input another model press 2
To quit program press <esc>
1
Distance to receiver ?  3000
The value of T is  5.5179 seconds
```

PROGRAM LISTING

```
      ' SEIS12    TRAVEL TIMES FOR LAYERED MEDIA
      CLS
      PRINT :PRINT "SEG PROGRAM SEIS12   TRAVEL TIMES FOR LAYERED MEDIA
      '
      PRINT :INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
      PRINT:IF Q THEN LPRINT
      DIM V(10),N(10),H(10)
      FOR I=1 TO 10:KEY I,"":NEXT
      CLS
      LOCATE 1,30:COLOR 0,7:PRINT " SEIS-12 ":COLOR 7,0
      LOCATE 3,10:PRINT "Calculation of Travel Times in Layered Media"
      LOCATE 4,10:PRINT "Based on calculator program by Ralphe Wiggins"
      LOCATE 5,10:PRINT "BASIC program by Doug Dodge"
      LOCATE 10,10:PRINT "This program can be used to compare actual                arrival times"
      LOCATE 11,10:PRINT "to predicted arrival times for a reflected                seismic wave"
      LOCATE 12,10:PRINT "The model has horizontal layers of uniform                thickness with"
      LOCATE 13,10:PRINT "constant velocity in each layer."
      LOCATE 18,20:COLOR 30,0:PRINT "Press any key to begin":COLOR 7,0
280   K$=INKEY$:IF K$="" GOTO 280
      ' start of program
      CLS
310 INPUT "Enter number of layers in model.  <Must be from 2 to 10>                    ",NM
      IF Q THEN LPRINT "Number of layers in model? <Must be from 2 to 10>              ",NM
      CLS:PRINT:PRINT:IF Q THEN LPRINT
      PRINT TAB(10) "Layer #" TAB(22) "ft" TAB(31) "ft/sec" TAB(39) "# OF
       TRAVERSES"
      FOR I=1 TO NM-1
      LAYER$(I)="Layer "+STR$(I): '  print the layer number on screen
      LOCATE I+4,10:PRINT LAYER$(I)
      ' prompt for input, print a reverse video block where input goes,
      ' and call a subroutine to put the input in the block.
      ' do this for thickness, velocity, number of traverses
      LOCATE 18,10:PRINT "Input thickness of ",LAYER$(I)," in feet"
      IF Q THEN LPRINT "Thickness of ",LAYER$(I)," in feet? ";
      LOCATE I+4,20:COLOR 0,7:PRINT SPACE$(8):COLOR 7,0
      ROW%=I+4:COL%=22:GOSUB 770:H(I)=INUM:IF Q THEN LPRINT H(I)
      LOCATE 18,10:PRINT SPACE$(60)
      LOCATE 18,10:PRINT "Input velocity of ",LAYER$(I)," in ft/s "
      LOCATE I+4,30:COLOR 0,7:PRINT SPACE$(8):COLOR 7,0
      COL%=32:GOSUB 770:V(I)=INUM
      IF Q THEN LPRINT "Velocity of ",LAYER$(I)," in ft/s ? ";V(I)
      LOCATE 18,10:PRINT SPACE$(60)
      LOCATE 18,10:PRINT "Input number of traverses of ",LAYER$(I)
      LOCATE I+4,40:COLOR 0,7:PRINT SPACE$(8):COLOR 7,0
      COL%=42:GOSUB 770:N(I)=INUM :' N(i) has the number of traverses
      IF Q THEN LPRINT "Input number of traverses of ",LAYER$(I);" ? ";N(I)
      LOCATE 18,10:PRINT SPACE$(60)
      NEXT
590 GOSUB 1060:'get t corresponding to x
      FORM$= "The value of T is ##.#### seconds"
      CLS:LOCATE 10,20:COLOR 15,0:PRINT USING FORM$;T:COLOR 7,0
      IF Q THEN LPRINT USING FORM$;T
      IF Q THEN LPRINT
      LOCATE 15,10:PRINT "To try another x press 1"
      IF Q THEN LPRINT "To try another x press 1"
      LOCATE 16,10:PRINT "To input another model press 2"
      IF Q THEN LPRINT "To input another model press 2"
      LOCATE 17,10:PRINT "To quit program press <esc>"
      IF Q THEN LPRINT "To quit program press <esc>"
700 K$=INKEY$:IF K$="" GOTO 700
      IF Q THEN LPRINT K$
      IF K$="1" GOTO 590 'Input another x and run sub to find t
      IF K$="2" THEN CLS:GOTO 310 'start the whole thing over
      IF K$=CHR$(27) THEN CLS:END
      GOTO 700
770 'THIS SUB ALLOWS PRINTING WITH BACKSPACING IN THE BOXED IN AREA
      XP$="":COLOR 0,7
```

```
790 LTR$=INKEY$:IF LTR$="" GOTO 790
    IF LEN(LTR$)>1 GOTO 790:'NO EXTENDED CODE
    IF LTR$=CHR$(8) GOTO 840
    IF ASC(LTR$)=13 THEN INUM=VAL(XP$):COLOR 7,0:RETURN
    IF ASC(LTR$)<48 OR ASC(LTR$)>57 GOTO 790 ' numbers only
840 IF LEN(XP$)=0 AND LTR$=CHR$(8) GOTO 790'LIMIT BACKSPACE
    IF LTR$=CHR$(8) THEN XP$=LEFT$(XP$,LEN(XP$)-1):GOTO 910
    IF LEN(XP$)=5 THEN LTR$="":GOSUB 960
    XP$=XP$+LTR$
    TEMP$=XP$
    LOCATE ROW%,COL%+LEN(XP$)-1:PRINT LTR$
910 LOCATE ROW%,COL%:PRINT XP$" ":' SHOW BACKSPACE
    GOTO 790
    COLOR 7,0:RETURN
    '-------------------------------------------------------------
960 'ERROR TRAPPING ROUTINE FOR  ENTRY
    BEEP
    LOCATE 10,42:COLOR 30,0:PRINT"MAXIMUM STRING LENGTH IS 5 SPACES"
    FOR I=1 TO 3000
    J=I
    NEXT I
    LOCATE 10,42:PRINT SPC(33):COLOR 7,0
    RETURN
    '-------------------------------------------------------------
1060 CLS
    LOCATE 10,40:INPUT "enter distance to receiver ",DIST
    IF Q THEN LPRINT "Distance to receiver ? ";DIST
    THETAMIN=0!:THETAMAX=1.57: 'search from 0 to π/2
    ' the next 7 lines try values of Θ and get the associated x values
    ' the x values are compared to DIST and Θ is changed so x gets closer
    ' to DIST.  When the change in Θ is small the sub exits.
1130 THETA =THETAMIN:GOSUB 1240:XMIN=SUM1:MINFLAG=FLAG: 'sub 810
     calculates x(Θ)
    THETA=THETAMAX:GOSUB 1240:XMAX=SUM1:MAXFLAG=FLAG
    THETAMID=(THETAMIN+THETAMAX)/2
    THETA=THETAMID:GOSUB 1240:XMID=SUM1:MIDFLAG=FLAG
    IF XMID >DIST OR MIDFLAG=1 THEN THETAMAX=THETAMID ELSE
     THETAMIN=THETAMID
    IF ABS(THETAMIN-THETAMAX)<.0001 THEN GOSUB 1320:RETURN
    GOTO 1130
    '*****************************************
    ' sub 810 rreturns Σ(Ni*Hi/√(1/Vi²-P²)
    ' if p²>1/V² flag is set to 1, indicates bad solution
1240 FLAG=0:P=SIN(THETA)/V(1)
    SUM1=0!
    FOR I=1 TO NM-1
    IF 1/V(I)/V(I)-P*P <0 THEN FLAG=1:RETURN
    SUM1=SUM1+N(I)*H(I)*P/SQR(1/V(I)/V(I)-P*P)
    NEXT
    RETURN
    '*****************************************
1320 '
    'sub to find t
    SUM2=0
    FOR I=1 TO NM-1
    SUM2=SUM2+N(I)*H(I)/SQR(V(I)*V(I)-P*P*V(I)^4)
    NEXT
    T=SUM2
    RETURN
```

PROGRAM SEIS13A
THREE-LAYER REFRACTION ANALYSIS

Program SEIS13A computes layer thicknesses and velocities for two layers on a half space given the intercept time, To, and one other distance-time point (X, Tx) for 3 events on a refraction profile. The equations used are shown in Figure 1. An example problem, its solution, and the program listing are given below. This program is modified from Danbom (MGHCP, 1981).

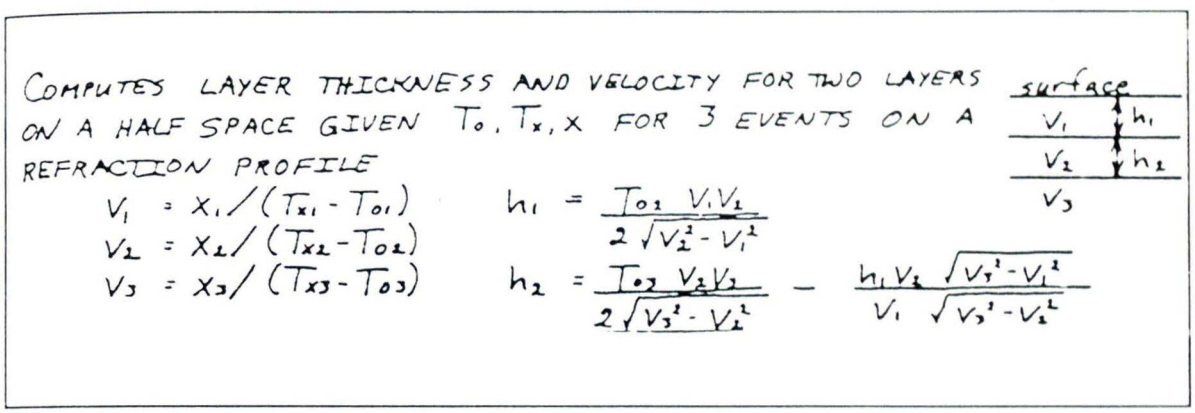


Figure 1. The equations used in program SEIS13A. After Danbom (MGHCP, 1981).

Example 1. A refraction time distance curve has three line segments. The intercept times are at 0.0 s, 0.020 s, and 0.080 s. At a distance of 915 ft, the three slopes pass through 1.3 s, 0.400 s, and 0.330 s, respectively. Find the velocities and thicknesses using a model consisting of two horizontal layers over a halfspace.

```
PROBLEM SOLUTION
SEG PROGRAM SEIS13A       3 LAYER REFRACTION ANALYSIS

Three intercept times?  0 , .02 , .08
X,Tx pair for direct wave ?  915 , 1.3
X,Tx pair for 1st refractor?  915 , .4
X,Tx pair for 2nd refractor?  915 , .33
V1 =  703.8462
V2 =  2407.895
V3 =  3660
H2 =  95.08189
```

PROGRAM LISTING

```
'SEIS13A        3 LAYER REFRACTION ANALYSIS
CLS
PRINT "SEG PROGRAM SEIS13A        3 LAYER REFRACTION ANALYSIS"
'
' This program computes the layer thicknesses and velocities for
' the case of two horizontal layers over a halfspace given the
' intercept time Ti, a shot-receiver distance x, and the time Tx at x
' for three events on a refraction profile.  This program is a
' modification of a TI program by S.  Danbom.
'
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
IF Q THEN LPRINT "SEG PROGRAM SEIS13A        3 LAYER REFRACTION ANALYSIS"
PRINT:IF Q THEN LPRINT
INPUT "Three intercept times";TI1,TI2,TI3
IF Q THEN LPRINT "Three intercept times? ";TI1","TI2","TI3
PRINT:INPUT "X,Tx pair for direct wave";X1,TX1
IF Q THEN LPRINT:LPRINT "X,Tx pair for direct wave ? ";X1","TX1
PRINT:INPUT "X,Tx pair for 1st refractor";X2,TX2
IF Q THEN LPRINT:LPRINT "X,Tx pair for 1st refractor? ";X2","TX2
PRINT:INPUT "X,Tx pair for 2nd refractor";X3,TX3
IF Q THEN LPRINT:LPRINT "X,Tx pair for 2nd refractor? ";X3","TX3
'
V1=X1/TX1:PRINT:PRINT "V1 = ";V1:IF Q THEN LPRINT:LPRINT "V1 = ";V1
V2=X2/(TX2-TI2):PRINT "V2 = ";V2:IF Q THEN LPRINT:LPRINT "V2 = ";V2
V3=X3/(TX3-TI3):PRINT "V3 = ";V3:IF Q THEN LPRINT:LPRINT "V3 = ";V3
'
H1=TI2*V1*V2/(2*SQR(V2^2-V1^2)):PRINT:PRINT "H1 = ";H1
H2=TI3*V2*V3/(2*SQR(V3^2-V2^2))-(H1*V2/V1)*SQR(V3^2-V1^2)/SQR(V3^2-V2^2)
PRINT:IF Q THEN LPRINT
PRINT "H2 = ";H2 :IF Q THEN LPRINT "H2 = ";H2
END
```

PROGRAM SEIS13B
MULTIPLE DIPPING SEISMIC REFRACTORS INTERPRETATION

This program interprets in-line seismic refraction data for the case of multiple dipping seismic refractors. A number of seismic refractors of velocities, V(I), dip with dips, D(I), under an overburden of velocity, V(1). Shots are fired at both ends, A and B, of an in-line array of geophones, and apparent velocities, VA(I), VB(I), and zero-intercept times, TA(I), TB(I), are measured on the resulting travel time graph. The program finds true velocities, V(I), and dips, D(I), and vertical depths, DA(I), DB(I), below shots A and B. Dips from shot A toward shot B are considered positive. This program and documentation are modified from Campbell (MGHCP, 1981).

The equations used are summarized in Figure 1. The equations involve the following assumptions: homogeneous and isotropic layers, planar boundaries, increasing velocity with deeper layers. In practice, depths and velocities estimated by seismic refraction surveys are accurate to 10-20% provided that low velocity layers are not present. The dips calculated are apparent dips along the geophone line. This program, as written, can accommodate up to nine layers over a halfspace. Further information on the algorithm used can be found in Mooney (Handbook of Engineering Geophysics, 1977, Bison Instruments, Inc., 5708 West 38th St., Minneapolis, Minn.).

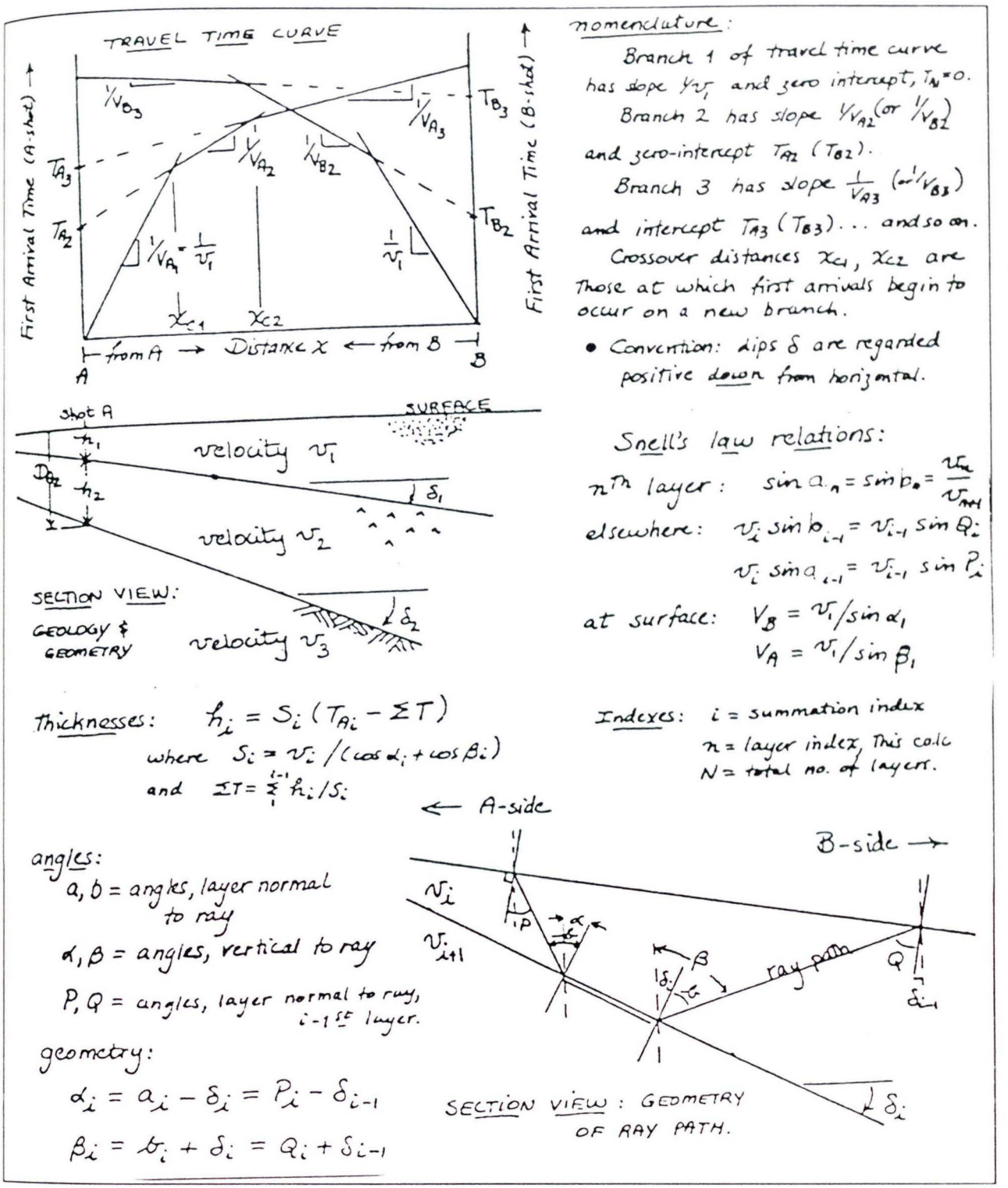
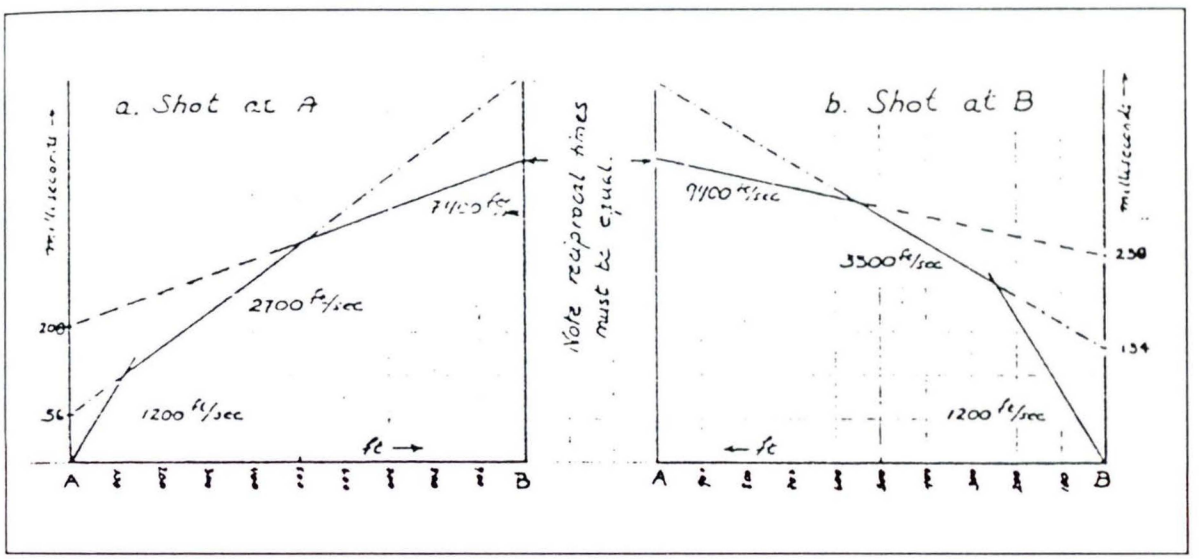


Figure 1. The equations used in program SEIS13B. Modified from Campbell (MGHCP, 1981).

The program includes an error check by prompting for the distance between the shotpoints. Simple trigonometric relations are used to check the consistency of the layer thickness and dips beneath the two shotpoints. If the reciprocal times are identical for both shots, and if the intercept times and velocities are carefully measured from the time-distance plots, then the plotting errors should be zero. In the example problem below, significant errors were made in reading values from the time-distance graphs. The program points these out as "plotting" errors. An example problem, its solution, and the program listing are given below.



Example 1. Interpret the reversed refraction profile shown above. After Campbell (MGHCP, 1981).

PROBLEM SOLUTION

SEG PROGRAM SEIS13B MULTIPLE DIPPING SEISMIC REFRACTORS--INTERPRETATION

Number of media present ? 3
Distance from shot A to shot B ? 1000
Velocity of overburden ? 1200

Refractor # 2 Apparent velocity pair VA,VB ? 2700 , 3300
Refractor # 3 Apparent velocity pair VA,VB ? 7400 , 9400

Refractor # 2 Intercept time pair TA,TB ? .056 , .134
Refractor # 3 Intercept time pair TA,TB ? .208 , .238

REFRACTION INTERPRETATION

LAYER	VELOCITY	DEPTH AT A	DIP ANGLE	DEPTH AT B
1	1200	0	0	0
2	2967.136	36.77453	2.532067	87.99619
3	8262.475	271.1061	-1.489363	235.7364

ERROR ANALYSIS

LAYER	PLOTTING ERROR
2	-7.955696 %
3	3.974803 %

To reduce above errors, be sure reciprocal times match and
that velocities and intercept times are carefully measured.

PROGRAM LISTING

```
' SEIS13B    MULTIPLE DIPPING SEISMIC REFRACTORS--INTERPRETATION
CLS
PRINT "SEG PROGRAM SEIS13B  MULTIPLE DIPPING SEISMIC REFRACTORS
 -INTERPRETATION"
'
' This program interprets in-line seismic refraction data for the          case
' of multiple dipping seismic refractors.  A number of seismic
' refractors of velocities V(I) dip with dips D(I) under an                 overburden
' of velocity V(1).  Shots are fired at both ends, A and B, of an           in-line
' array of geophones, and apparent velocities VA(I), VB(I) and zero-
' intercept times TA(I), TB(I) are measured on the resulting travel
' time graph.  Using these data, the program finds true velocities                  V(I)
' and dips D(I) and vertical depths DA(I),DB(I) below shots A and B.
' Dips from shot A toward shot B are considered positive.
' This program is modified from a TI program by D.L.  Campbell.
'
'
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
IF Q THEN LPRINT "SEG PROGRAM SEIS13B  MULTIPLE DIPPING SEISMIC
 REFRACTORS -INTERPRETATION"
PRINT:IF Q THEN LPRINT
DEF FNASIN(X)=57.296*ATN(X/SQR(1-X*X))
DEF FNSN(X)=SIN(.017453*X)
DEF FNCS(X)=COS(.017453*X)
DEF FNTN(X)=TAN(.017453*X)
INPUT "Number of media present";M
IF Q THEN LPRINT "Number of media present ? ";M
INPUT "Distance from shot A to shot B";DIST
IF Q THEN LPRINT "Distance from shot A to shot B ? ";DIST
INPUT "Velocity of overburden";V(1):VA(1)=V(1):VB(1)=V(1)
IF Q THEN LPRINT "Velocity of overburden ? ";V(1)
PRINT:IF Q THEN LPRINT
FOR I=2 TO M
PRINT "Refractor #";I;:INPUT "Apparent velocity pair VA,VB";VA(I),VB(I)
IF Q THEN LPRINT "Refractor #";I;:LPRINT "Apparent velocity pair          VA,VB ? " VA(I)","VB(I)
IF VA(I)<=VA(I-1) OR VB(I)<=VB(I-1) THEN PRINT "V's must increase w.
 depth"
NEXT
PRINT :IF Q THEN LPRINT
FOR I=2 TO M
PRINT "Refractor #";I;:INPUT "Intercept time pair TA,TB";TA(I),TB(I)
IF Q THEN LPRINT "Refractor #";I;:LPRINT "Intercept time pair TA,TB ";TA(I)","TB(I)
NEXT
PRINT:IF Q THEN LPRINT
TA(1)=0:TB(1)=0
'
'
FOR N=1 TO M-1   'Do for each layer above halfspace
ALFA(1)=FNASIN(V(1)/VB(N+1)):BETA(1)=FNASIN(V(1)/VA(N+1))
IF N=1 THEN SUMT(N)=0:GOTO 650
SUMTA(N)=HA(1)/(V(1)/(FNCS(ALFA(1))+FNCS(BETA(1))))
SUMTB(N)=HB(1)/(V(1)/(FNCS(ALFA(1))+FNCS(BETA(1))))
FOR I=2 TO N
ALFA(I)=FNASIN((V(I)/V(I-1))*FNSN(ALFA(I-1)+D(I-1)))-D(I-1)
BETA(I)=FNASIN((V(I)/V(I-1))*FNSN(BETA(I-1)-D(I-1)))+D(I-1)
IF I<>N THEN
 SUMTA(N)=SUMTA(N)+HA(I)/(V(I)/(FNCS(ALFA(I)+FNCS(BETA(I)))
IF I<>N THEN
 SUMTB(N)=SUMTB(N)+HB(I)/(V(I)/(FNCS(ALFA(I)+FNCS(BETA(I)))
NEXT I
650  '
D(N)=-(ALFA(N)-BETA(N))/2      'Dip angle
ICR(N)=(ALFA(N)+BETA(N))/2    'Critical angle
V(N+1)=V(N)/FNSN(ICR(N))      'Find velocity of next layer
S(N)=V(N)/(FNCS(ALFA(N))+FNCS(BETA(N)))
HA(N)=S(N)*(TA(N+1)-SUMTA(N))    'Vertical thickness under A
HB(N)=S(N)*(TB(N+1)-SUMTB(N))    'Vertical thickness under B
```

```
DEPTHA(N)=DEPTHA(N-1)+HA(N)     'Depth to base of layer N under A
DEPTHB(N)=DEPTHB(N-1)+HB(N)     'Depth to base of layer N under A
CHECK(N)=DEPTHA(N)+DIST*FNTN(D(N))   'Check depth under shot B
ER(N)=(CHECK(N)-DEPTHB(N))/DEPTHB(N)*100
NEXT N
INPUT "Display results <Y/N>";A$
IF A$="Y" OR A$="y" THEN 790 ELSE END
790 CLS:IF Q THEN LPRINT
PRINT "REFRACTION INTERPRETATION":PRINT
IF Q THEN LPRINT "REFRACTION INTERPRETATION":LPRINT
PRINT "LAYER","VELOCITY","DEPTH AT A","DIP ANGLE","DEPTH AT B"
IF Q THEN LPRINT "LAYER","VELOCITY","DEPTH AT A","DIP ANGLE","DEPTH AT B"
FOR I=1 TO M
PRINT I,V(I),DEPTHA(I-1),D(I-1),DEPTHB(I-1)
IF Q THEN LPRINT I,V(I),DEPTHA(I-1),D(I-1),DEPTHB(I-1)
NEXT
PRINT:PRINT:PRINT "ERROR ANALYSIS":PRINT
IF Q THEN LPRINT:LPRINT:LPRINT "ERROR ANALYSIS":LPRINT
PRINT "LAYER","PLOTTING ERROR"
IF Q THEN LPRINT "LAYER","PLOTTING ERROR"
PRINT:FOR I=1 TO M-1:PRINT I+1,ER(I);" %":NEXT
IF Q THEN LPRINT:FOR I=1 TO M-1:LPRINT I+1,ER(I);" %":NEXT
PRINT:PRINT "To reduce above errors, be sure reciprocal times match and"
IF Q THEN LPRINT:LPRINT "To reduce above errors, be sure reciprocal times match and"
PRINT "that velocities and intercept times are carefully measured."
IF Q THEN LPRINT "that velocities and intercept times are carefully  measured."
END
```

PROGRAM SEIS13C
MULTIPLE DIPPING SEISMIC REFRACTORS--DESIGN

Program SEIS13C calculates multi-layer refraction travel time curves. Functions are provided to calculate apparent velocities, time intercepts, and crossover distances so as to aid a geophysicist designing a refraction seismic survey. Low velocity layers may be included in the model. This program and documentation are based on Campbell (MGHCP, 1981).

The equations used are shown on Figure 1. The program can handle up to 9 layers over a halfspace. The assumptions are constant velocity in each layer and planar boundaries between layers. The dips entered are positive down from the horizontal in a direction from shot A toward shot B. The dips are apparent dips in the direction of the geophone line. The program cannot handle pinchouts of layers beneath the geophone line. For further information on the use of this type of analysis, see Mooney (Handbook of Engineering Geophysics, 1977, Bison Instruments, Inc., Minneapolis, Minn.). An example problem, its solution, and the program listing follow.

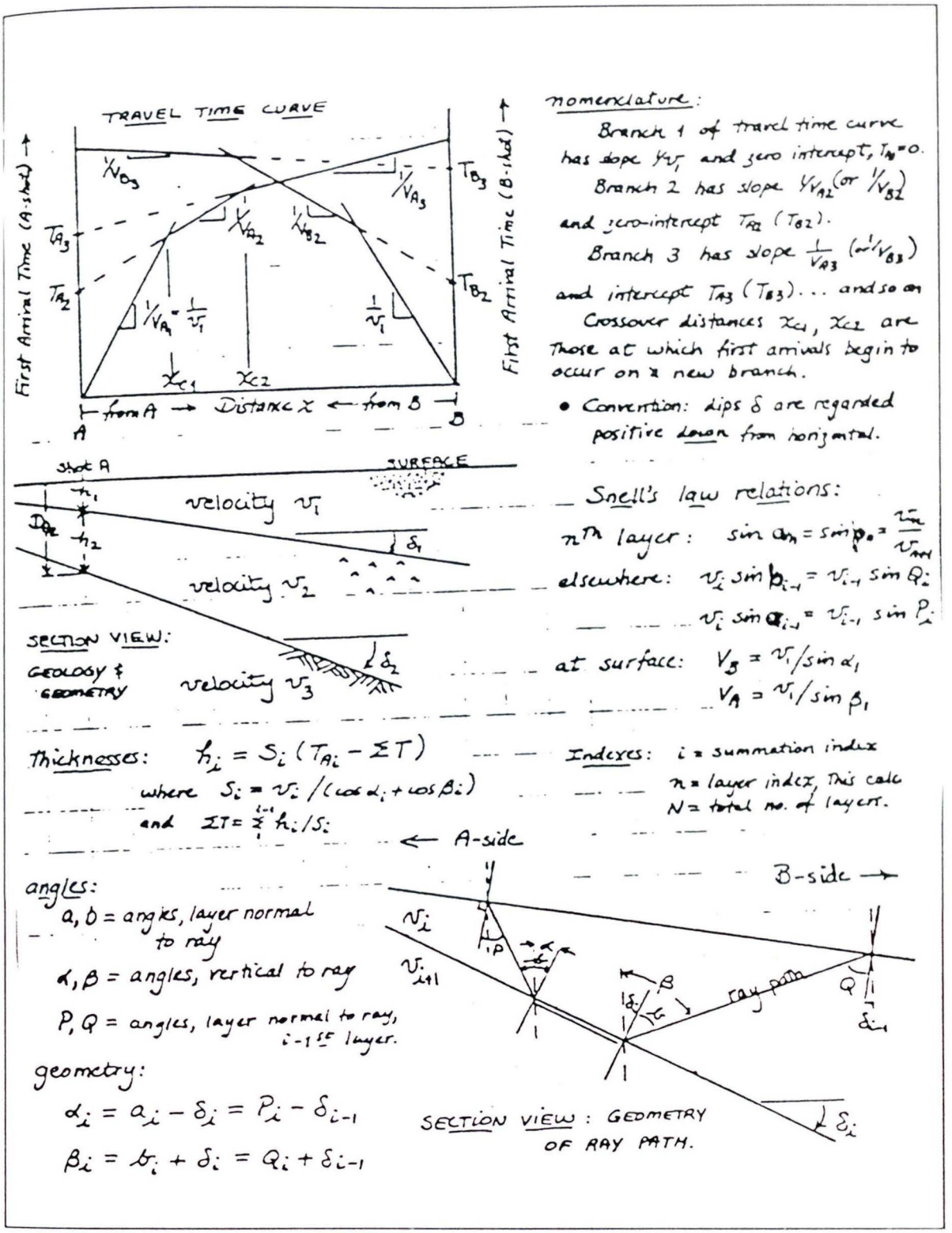
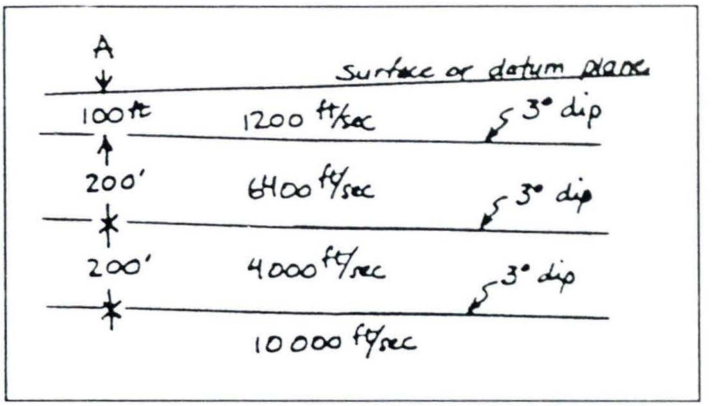


Figure 1. The equations used in program SEIS13C as modified from Campbell (MGHCP, 1981).



Example 1. Determine the parameters of a reversed refraction profile over the model shown above. After Campbell (MGHCP, 1981).

```
PROBLEM SOLUTION

Number of layers present including overburden and halfspace ?  4
Distance from shot A to shot B ?  1000

Shot A
Layer # 1
Thickness, Velocity, Dip of base? 100 , 1200 , 3
Layer # 2
Thickness, Velocity, Dip of base? 200 , 6400 , 3
Layer # 3
Thickness, Velocity, Dip of base? 200 , 4000 , 3
Layer # 4 (halfspace)
Velocity?  10000
LVL PRESENT

SHOT A     Reciprocal time is  447.877  ms

Slope #       Intercept      Apparent       Critical       Critical
                Time ms       Velocity      Distance       Time ms
 1              0             1200           0              0
 2              163.4865      5028.335       257.6781       214.7317
 3              163.4865      5028.335       257.6781       214.7317
 4              304.7202      6985.345       2534.879       667.6055

SHOT B     Reciprocal time is  447.877  ms

Slope #       Intercept      Apparent       Critical       Critical
                Time ms       Velocity      Distance       Time ms
 1              0             1200           0              0
 2              249.1647      8834.33        345.9955       288.3296
 3              249.1647      8834.33        345.9955       288.3296
 4              391.3152      17679.73       2510.034       533.2875
```

PROGRAM LISTING

```
'SEIS13C      REFRACTION SEISMIC DESIGN
CLS
PRINT "SEG PROGRAM SEIS13C    REFRACTION SEISMIC DESIGN"
IF Q1 THEN LPRINT "SEG PROGRAM SEIS13C    REFRACTION SEISMIC
 DESIGN"
' This program calculates multi-layer refraction travel time curves.
' Functions are provided to calculate apparent velocities, time
' intercepts, and crossover distances so as to aid a geophysicist
' designing a refraction seismic survey.  Low velocity layers may be
' included in the model.  This program is based on a TI program by
' D.  Campbell.
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q1=1
IF Q THEN LPRINT "SEG PROGRAM SEIS13C    REFRACTION SEISMIC
 DESIGN"
DIM V(10)    'True velocity of layer I
DIM VA(10),VB(10)  ' Apparent velocities for shots A and B.
DIM TA(10),TB(10)  ' Intercept times for shots A and B
DIM RA(10),RB(10)    'Reciprocal times for shots A and B (Should be equal)
DIM XA(10),XB(10)  ' Crossover distances for shots A and B
DIM D(10)          ' Dip of base of layer I
DIM DA(10)         ' Vertical depth to base of layer I
' Dips from shot A toward shot B are considered positive.
'
DEF FNASIN(X)=57.296*ATN(X/SQR(1-X*X))
DEF FNSN(X)=SIN(.017453*X)
DEF FNCS(X)=COS(.017453*X)
DEF FNTN(X)=TAN(.017453*X)
PRINT:IF Q1 THEN LPRINT
INPUT "Number of layers present including overburden and halfspace";M
IF Q1 THEN LPRINT "Number of layers present including
                                          overburden and halfspace ? ";M
  INPUT "Distance from shot A to shot B? ";DIST
IF Q1 THEN LPRINT "Distance from shot A to shot B ? "; DIST
PRINT:IF Q1 THEN LPRINT
PRINT "Shot A"
IF Q1 THEN LPRINT "Shot A"
FOR I=1 TO M-1
PRINT "Layer #";I:INPUT "Thickness, Velocity, Dip of base";HA(I),V(I),D(I)
IF Q1 THEN LPRINT "Layer #";I:LPRINT "Thickness, Velocity,
                                        Dip of base";HA(I)","V(I)","D(I)
NEXT
PRINT "Layer #";M;"(halfspace)":INPUT "Velocity";V(M):PRINT
IF Q1 THEN LPRINT "Layer #";M;"(halfspace)":LPRINT "Velocity? ";V(M):LPRINT
VA(1)=V(1):VB(1)=V(1)
'Calculate thicknesses at shot B
FOR I= 1 TO M-1
HB(I)=HA(I)+DIST*FNTN(D(I))-DIST*FNTN(D(I-1))
NEXT I
'
FOR N=1 TO M-1  'Do for each layer above halfspace
IF V(N+1)<=V(N) THEN 580 ELSE 640
580  'LVL
PRINT "LVL PRESENT"
IF Q1 THEN LPRINT "LVL PRESENT"
VA(N+1)=VA(N):VB(N+1)=VB(N):TA(N+1)=TA(N):TB(N+1)=TB(N)
XA(N+1)=XA(N):XB(N+1)=XB(N):RB(N+1)=RB(N):RA(N+1)=RA(N)
GOTO 960
640  'Find alfa and beta in each layer
ALFA(N)=FNASIN(V(N)/V(N+1))-D(N)
BETA(N)=FNASIN(V(N)/V(N+1))+D(N)
IF N=1 THEN 810
FOR I=N TO 2 STEP -1
P=ALFA(I)+D(I-1):Q=BETA(I)-D(I-1)
B=FNASIN(V(I-1)*FNSN(Q)/V(I))
A=FNASIN(V(I-1)*FNSN(P)/V(I))
```

```
ALFA(I-1)=A-D(I-1)
BETA(I-1)=B+D(I-1)
NEXT I
SUMTA(N)=HA(1)/(V(1)/(FNCS(ALFA(1))+FNCS(BETA(1))))
SUMTB(N)=HB(1)/(V(1)/(FNCS(ALFA(1))+FNCS(BETA(1))))
FOR I=2 TO N
IF I<>N THEN
 SUMTA(N)=SUMTA(N)+HA(I)/(V(I)/(FNCS(ALFA(I))+FNCS(BETA(I))))
IF I<>N THEN
 SUMTB(N)=SUMTB(N)+HB(I)/(V(I)/(FNCS(ALFA(I))+FNCS(BETA(I))))
NEXT I
'
'
'Calculate apparent velocities
VB(N+1)=V(1)/FNSN(ALFA(1))
VA(N+1)=V(1)/FNSN(BETA(1))
S(N)=V(N)/(FNCS(ALFA(N))+FNCS(BETA(N)))
'Calculate intercept times
TA(N+1)=HA(N)/S(N)+SUMTA(N)
TB(N+1)=HB(N)/S(N)+SUMTB(N)
'Calculate cross-over times
XA(N+1)=(TA(N+1)-TA(N))/(1/VA(N)-1/VA(N+1))
XB(N+1)=(TB(N+1)-TB(N))/(1/VB(N)-1/VB(N+1))
'Calculate reciprocal times for each refractor
RA(N+1)=TA(N+1)+DIST/VA(N+1)
RB(N+1)=TB(N+1)+DIST/VB(N+1)
NEXT N
RA(1)=DIST/VA(1):RB(1)=DIST/VB(1)
INPUT "Display results <Y/N>";A$
IF A$="Y" OR A$="y" THEN 1000 ELSE END
CLS :IF Q1 THEN LPRINT
PRINT:PRINT "SHOT A     Reciprocal time is ";RA(M)*1000;" ms"
IF Q1 THEN LPRINT:LPRINT "SHOT A     Reciprocal time is ";RA(M)*1000;" ms"
PRINT :IF Q1 THEN LPRINT
PRINT "Slope #","Intercept","Apparent","Critical","Critical"
IF Q1 THEN LPRINT "Slope #","Intercept","Apparent","Critical","Critical"
PRINT " "," Time ms"," Velocity","Distance","Time ms"
IF Q1 THEN LPRINT " "," Time ms"," Velocity","Distance","Time ms"
PRINT:IF Q1 THEN LPRINT
FOR I=1 TO M
PRINT I, TA(I)*1000,VA(I),XA(I),(TA(I)+XA(I)/VA(I))*1000
IF Q1 THEN LPRINT I, TA(I)*1000,VA(I),XA(I),(TA(I)+XA(I)/VA(I))*1000
NEXT
PRINT :IF Q1 THEN LPRINT
PRINT:PRINT "SHOT B     Reciprocal time is ";RB(M)*1000;" ms"
IF Q1 THEN LPRINT:LPRINT "SHOT B     Reciprocal time is ";RB(M)*1000;" ms"
PRINT :IF Q1 THEN LPRINT
PRINT "Slope #","Intercept","Apparent","Critical","Critical"
IF Q1 THEN LPRINT "Slope #","Intercept","Apparent","Critical","Critical"
PRINT " "," Time ms"," Velocity","Distance","Time ms"
IF Q1 THEN LPRINT " "," Time ms"," Velocity","Distance","Time ms"
PRINT:IF Q1 THEN LPRINT
FOR I=1 TO M
PRINT I, TB(I)*1000,VB(I),XB(I),(TB(I)+XB(I)/VB(I))*1000
IF Q1 THEN LPRINT I, TB(I)*1000,VB(I),XB(I),(TB(I)+XB(I)/VB(I))*1000
NEXT
PRINT:IF Q1 THEN LPRINT
END
```

PROGRAM SEIS13D
ELEVATION CORRECTIONS
IN SHALLOW SEISMIC REFRACTION SURVEYS

This program computes elevation corrections for shallow seismic refraction surveys. Arrival times in seismic refraction surveys are influenced by the seismic velocities of the earth materials, the acoustic impedance, contrast between these materials, and the locations of the geophones with respect to the shotpoint. Commonly, the shotpoint is at a different elevation from the geophones, and the geophones are at different elevations from one another. The differences in elevation can lead to time-distance curves that are not representative of the subsurface conditions especially in shallow seismic refraction surveys. The accuracy of the interpretation can be improved by correcting the shotpoint and geophone elevations to a common datum below the surface but above the interface between the upper two layers. This program and documentation are modified from Cummings and Ryland (MGHCP, 1981). The equations used in the program are from Dobrin (Introduction to Geophysical Prospecting, 3rd ed.: New York, McGraw-Hill Book Co., Inc., 630 p). Figure 1 shows the symbols used. An example problem, its solution, and the program listing follow.

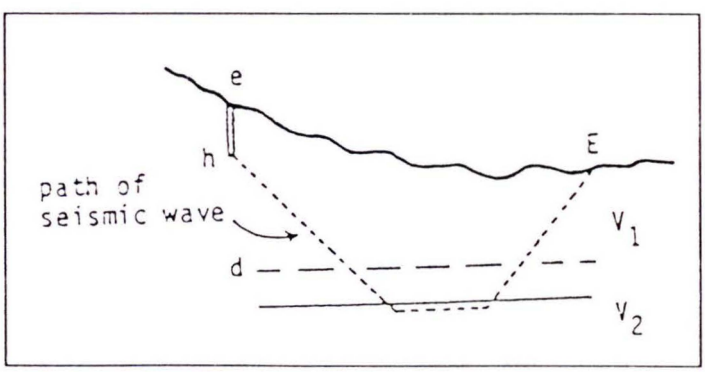


Figure 1. The elevation correction for the two-layer case. After Cummings and Ryland (MGHCP, 1981).

V_1= 1100 ft/sec

V_2= 5300 ft/sec

e= 745 ft above sea level

h= 5 ft

d= 700 ft above sea level

E= 731,712,725,742,740,748

Example 1. Determine the elevation correction for the geophone elevations given above. After Cummings and Ryland (MGHCP, 1981).

PROBLEM SOLUTION

```
PROGRAM SEIS13D  ELEVATION CORRECTIONS IN SHALLOW SEISMIC REFRACTION SURVEYS
You may enter data from the keyboard or use a pre-existing ASCII file.
To use a pre-existing file type (1)
To enter data from keyboard type (2)
1
The following data are from file data.13D
 731
 712
 725
 742
 740
 748
Enter V1 and V2?  1100 , 5300
Enter shotpoint elevation?  745
Enter depth of shot below surface?          5
Enter elevation of reference horizon?       700
Geophone elevation          Correction to time

 731            6.313998E-02
 712            4.624337E-02
 725            5.780421E-02
 742            7.292223E-02
 740            7.114365E-02
 748            7.825801E-02

SEG PROGRAM SEIS13D  ELEVATION CORRECTIONS IN SHALLOW SEISMIC REFRACTION
SURVEYS
```

```
You may enter data from the keyboard or use a pre-existing ASCII file.
To use a pre-existing file type (1)
To enter data from keyboard type (2)
2
Input geophone elevation?    731
Input geophone elevation?    712
Input geophone elevation?    725
Input geophone elevation?    742
Input geophone elevation?    740
Input geophone elevation?    748
Enter V1 and V2?  1100 , 5300
Enter shotpoint elevation?  745
Enter depth of shot below surface?          5
Enter elevation of reference horizon?       700

Geophone elevation          Correction to time
 731            6.313998E-02
 712            4.624337E-02
 725            5.780421E-02
 742            7.292223E-02
 740            7.114365E-02
 748            7.825801E-02
```

PROGRAM LISTING

```
        'SEIS13D  ELEVATION CORRECTIONS IN SHALLOW SEISMIC REFRACTION
         SURVEYS
        CLS
        PRINT "SEG PROGRAM SEIS13D  ELEVATION CORRECTIONS IN SHALLOW
         SEISMIC REFRACTION SURVEYS"
        ' This program calculates elevation corrections for shallow seismic
        ' refraction surveys.  This program is modified from an HP program
        ' by D.C.  Campbell and S.L.  Ryland.
        PRINT:INPUT "Hard copy <Y/N>";A$:IF A$="Y" OR A$="y" THEN Q=1
        PRINT:IF Q THEN LPRINT
        IF Q THEN LPRINT "SEG PROGRAM SEIS13D  ELEVATION CORRECTIONS IN
         SHALLOW SEISMIC REFRACTION SURVEYS"
        KEY OFF
        DIM Z(200),T(200)
        CLS :IF Q THEN LPRINT
        LOCATE 4,37:COLOR 0,7:PRINT "SEIS-13D":COLOR 7,0
        LOCATE 6,15:PRINT "ELEVATION CORRECTIONS IN SHALLOW REFRACTION
         SURVEYS"
        LOCATE 7,15:PRINT "based on calculator program by Cummings and Ryland"
        PRINT:PRINT:PRINT:IF Q THEN LPRINT
        PRINT "You may enter data from the keyboard or use a pre-existing ASCII file."
        IF Q THEN LPRINT "You may enter data from the keyboard or use a
         pre-existing ASCII file."
        PRINT "TO CONTINUE PRESS ANY KEY"
310     B$=INKEY$:IF B$="" THEN GOTO 310
        CLS :IF Q THEN LPRINT
        LOCATE 5,30:PRINT"To use a pre-existing file type (1)"
        IF Q THEN LPRINT"To use a pre-existing file type (1)"
        LOCATE 7,30:PRINT"To enter data from keyboard type (2)"
        IF Q THEN LPRINT"To enter data from keyboard type (2)"
370     K$=INKEY$:IF K$="" GOTO 370
        IF Q THEN LPRINT K$:LPRINT
        IF K$="1" THEN GOSUB 640:GOSUB 430:END
        IF K$="2" THEN CLS:GOSUB 840:GOSUB 430:END
        GOTO 370
430     CLS : IF Q THEN LPRINT
        INPUT "Enter V1 and V2 ",V1,V2
        IF Q THEN LPRINT "Enter V1 and V2? ";V1","V2
```

```
      INPUT "Enter shotpoint elevation ";E
      IF Q THEN LPRINT "Enter shotpoint elevation? " ;E
      INPUT "Enter depth of shot below surface ";H
      IF Q THEN LPRINT "Enter depth of shot below surface? ",H
      INPUT "Enter elevation of reference horizon ",D
      IF Q THEN LPRINT "Enter elevation of reference horizon? ",D
      B=SQR(V2*V2-V1*V1)/V1/V2 :P=E-H-2*D
      CLS:IF Q THEN LPRINT
      LOCATE 4,10:PRINT "Geophone elevation":LOCATE 4,35:PRINT "Correction
       to time"
      IF Q THEN LPRINT "Geophone elevation", "Correction to time"
      FOR I=1 TO N
      T(I)=(P+Z(I))*B
      PRINT TAB(16) Z(I) TAB(35) T(I)
      IF Q THEN LPRINT Z(I), T(I)
      NEXT
      RETURN
640   'subroutine to use pre-existing data file
      CLS :IF Q THEN LPRINT
      PRINT "YOUR DATA FILE SHOULD CONTAIN GEOPHONE ELEVATIONS ONE
       TO"
      IF Q THEN LPRINT "YOUR DATA FILE SHOULD CONTAIN GEOPHONE
       ELEVATIONS ONE TO"
      PRINT "THE LINE.  THE FILE SHOULD BE IN ASCII FORMAT AND THE UNITS"
      PRINT "OF ELEVATION SHOULD CORRESPOND TO THE UNITS OF VELOCITY
       USED"
      IF Q THEN LPRINT "OF ELEVATION SHOULD CORRESPOND TO THE UNITS
       OF VELOCITY USED"
      PRINT:IF Q THEN LPRINT
      INPUT "ENTER THE NAME OF DATA FILE CONTAINING TIME-DISTANCE PAIRS    ",FILE$
      IF Q THEN LPRINT "ENTER THE NAME OF DATA FILE CONTAINING
       TIME-DISTANCE PAIRS ? ",FILE$
      OPEN FILE$ FOR INPUT AS #1
      IF Q THEN LPRINT:LPRINT "The following data are from file ";FILE$:LPRINT
      I=1
      WHILE NOT EOF(1)
      INPUT#1,Z(I)
      IF Q THEN LPRINT Z(I)
      I=I+1:N=I-1
      WEND
      RETURN
840   ' subroutine to get data from keyboard
      N=1
860   LOCATE 18,5:PRINT SPACE$(50)
      LOCATE 19,5:PRINT SPACE$(50)
      LOCATE 6,22:PRINT SPACE$(10):LOCATE 6,10:INPUT "Input geophone
       elevation ",Z(N)
      IF Q THEN LPRINT "Input geophone elevation? ",Z(N)
      N=N+1
      LOCATE 18,5:COLOR 0,7:PRINT "To input another press <return>"
      LOCATE 19,5:PRINT"To return to main program press <Esc>.":COLOR 7,0
930   K$=INKEY$:IF K$="" GOTO 930
      IF Q THEN LPRINT
      IF K$=CHR$(13) GOTO 860
      IF K$=CHR$(27) THEN CLS:N=N-1:RETURN
      GOTO 930
      END
```

PROGRAM SEIS13E
COMBINED ELEVATION AND WEATHERED LAYER CORRECTION IN SHALLOW SEISMIC REFRACTION SURVEYS

Program SEIS13E computes a combined elevation and weathered layer correction for shallow seismic refraction surveys. The equation used in this program is for the case where the shotpoint is located below the weathered layer. The equation used and an explanatory diagram are shown in Figure 1. The equation is modified from Dobrin (Introduction to Geophysical Prospecting, 3rd Edition: New York, McGraw-Hill Book Co., Inc., 630 p.). This program and documentation are modified from Cummings and Ryland (MGHCP, 1981). An example problem, its solution, and the program listing follow.

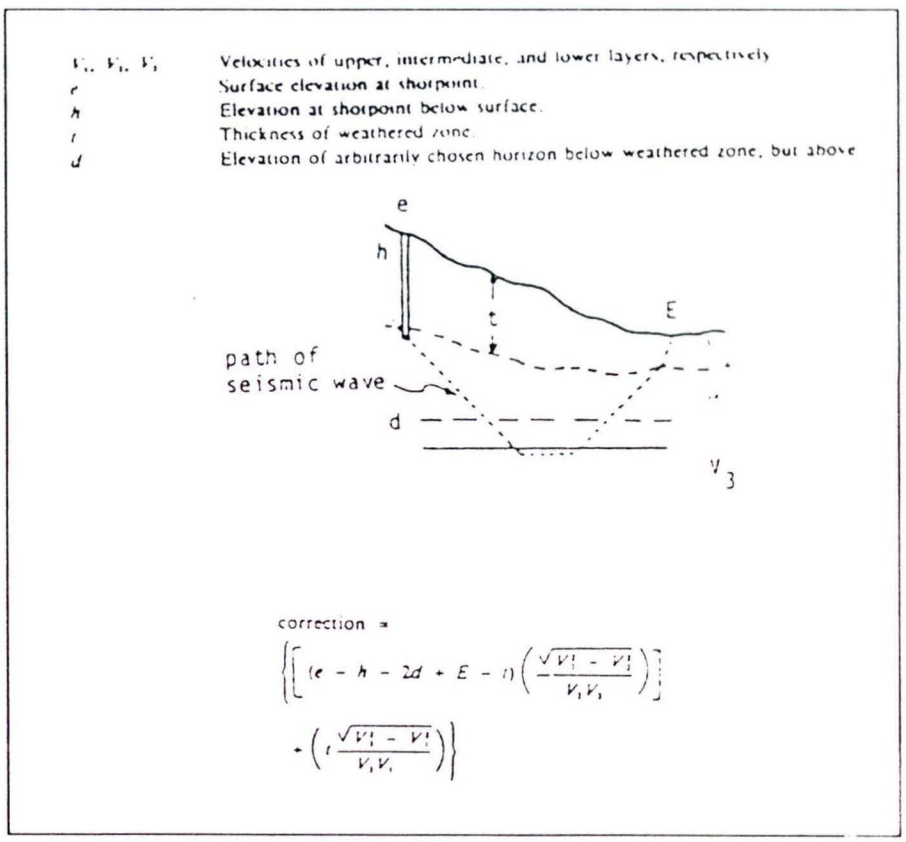


Figure 1. The equation used in program SEIS13E. After Cummings and Ryland (MGHCP, 1981).

V1 = 930 ft/s V2 = 1350 ft/s V3 = 7300 ft/s

t = 6 ft (Relatively constant on survey area)

e = 1248 ft h = 9 ft d = 915 ft

E = 920, 925, 922, 919, 915, 919, 927, 924, 921, 917, 920, 923

Example 1. Compute the combined elevation and weathered layer correction for the data given above. After Cummings and Ryland (MGHCP, 1981).

PROBLEM SOLUTION

```
SEG PROGRAM SEIS13E COMBINED ELEVATION AND WEATHERED LAYER CORRECTION  IN
SHALLOW SEISMIC REFRACTION SURVEYS

You may enter data from the keyboard or use a pre-existing ASCII file.

To use a pre-existing file type (1)
To enter data from keyboard type (2)
1

YOUR DATA FILE SHOULD CONTAIN GEOPHONE ELEVATIONS ONE TO
THE LINE.  THE FILE SHOULD BE IN ASCII FORMAT AND THE UNITS
OF ELEVATION SHOULD CORRESPOND TO THE UNITS OF VELOCITY USED

ENTER THE NAME OF DATA FILE CONTAINING TIME-DISTANCE PAIRS?          DATA.13E

<The following data is in external file: DATA.13E>
 920 925 919 915 919 927 924 921 917 920 923

Enter V1, V2, and V3?   930 , 1350 , 7300
Enter thickness of weathered layer?        6
Enter shotpoint elevation?  1248
Enter depth of shot below surface?         9
Enter elevation of reference horizon?      915
```

```
Geophone elevation       Correction to time

 920                          .2415314
 925                          .2451712
 919                          .2408035
 915                          .2378916
 919                          .2408035
 927                          .2466272
 924                          .2444433
 921                          .2422594
 917                          .2393475
 920                          .2415314
 923                          .2437153

<Below, the problem is solved again using keyboard input>

SEG PROGRAM SEIS13E COMBINED ELEVATION AND WEATHERED LAYER CORRECTION IN
SHALLOW SEISMIC REFRACTION SURVEYS

You may enter data from the keyboard or use an ASCII file.

To use a pre-existing file type  (1)
To enter data from keyboard type (2)
2
Input elevation?  920
Input elevation?  925
Input elevation?  922
Input elevation?  919
Input elevation?  927
Input elevation?  924
Input elevation?  921
Input elevation?  917
Input elevation?  920
Input elevation?  923

Enter V1, V2, and V3?   930 , 1350 , 7300
Enter thickness of weathered layer?        6
Enter shotpoint elevation?  1248
Enter depth of shot below surface?         9
Enter elevation of reference horizon?      915
Geophone elevation  Correction to time
 920                          .2415314
 925                          .2451712
 922                          .2429874
 919                          .2408035
 927                          .2466272
 924                          .2444433
 921                          .2422594
 917                          .2393475
 920                          .2415314
 923                          .2437153
```

```
 COMBINED ELEVATION AND WEATHERED LAYER CORRECTION
' IN SHALLOW SEISMIC REFRACTION SURVEYS
'
CLS
PRINT "SEG PROGRAM SEIS13E COMBINED ELEVATION AND WEATHERED
 LAYER CORRECTION"
PRINT " IN SHALLOW SEISMIC REFRACTION SURVEYS"
'
' This program computes a combined elevation and weathered layer  correction
' for shallow seismic refraction surveys.  This program is modified                from an
' HP program by D.  Cummings and  L.  Ryland.
'
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
PRINT:IF Q THEN LPRINT
IF Q THEN LPRINT "SEG PROGRAM SEIS13E COMBINED ELEVATION AND
 WEATHERED LAYER CORRECTION"
IF Q THEN LPRINT " IN SHALLOW SEISMIC REFRACTION SURVEYS"
IF Q THEN LPRINT
KEY OFF
DIM Z(200),T(200)
CLS
LOCATE 4,37:COLOR 0,7:PRINT "SEIS-13E":COLOR 7,0
LOCATE 6,15:PRINT "COMBINED ELEVATION AND WEATHERED LAYER
 CORRECTION"
LOCATE 7,15:PRINT "based on calculator program by Cummings and Ryland"
PRINT:PRINT:PRINT
PRINT "You may enter data from the keyboard or use a pre-existing ASCII file."
IF Q THEN LPRINT "You may enter data from the keyboard or use a
 pre-existing ASCII file."
PRINT "TO CONTINUE PRESS ANY KEY"
360  B$=INKEY$:IF B$="" THEN GOTO 360
     CLS:IF Q THEN LPRINT
     LOCATE 5,30:PRINT"To use a pre-existing file type (1)"
     IF Q THEN LPRINT"To use a pre-existing file type (1)"
     LOCATE 7,30:PRINT"To enter data from keyboard type (2)"
     IF Q THEN LPRINT"To enter data from keyboard type (2)"
420  K$=INKEY$:IF K$="" GOTO 420
     IF Q THEN LPRINT K$
     IF K$="1" THEN GOSUB 720:GOSUB 480:END
     IF K$="2" THEN CLS:GOSUB 930:GOSUB 480:END
     GOTO 420
     '
480  'process data
     CLS:IF Q THEN LPRINT
     INPUT "Enter V1, V2, and V3 ",V1,V2,V3
     IF Q THEN LPRINT "Enter V1, V2, and V3?  ";V1","V2","V3
     INPUT "Enter thickness of weathered layer ",T
     IF Q THEN LPRINT "Enter thickness of weathered layer? ",T
     INPUT "Enter shotpoint elevation ";E
     IF Q THEN LPRINT "Enter shotpoint elevation? ";E
     INPUT "Enter depth of shot below surface ",H
     IF Q THEN LPRINT "Enter depth of shot below surface? ",H
     INPUT "Enter elevation of reference horizon ",D
     IF Q THEN LPRINT "Enter elevation of reference horizon? ",D
     B=SQR(V3*V3-V2*V2)/V2/V3
     C=T*SQR(V3*V3-V1*V1)/V3/V1
     P=E-H-2*D-T
     CLS :IF Q THEN LPRINT
     PRINT "Geophone elevation    Correction to time"
     IF Q THEN LPRINT "Geophone elevation  Correction to time"
     FOR I=1 TO N
     T(I)=(P+Z(I))*B+C
     IF Q THEN LPRINT  Z(I),,T(I)
     PRINT  Z(I),,T(I)
     NEXT
     RETURN
720  'subroutine to use pre-existing data file
```

```
      CLS:IF Q THEN LPRINT
      PRINT "YOUR DATA FILE SHOULD CONTAIN GEOPHONE ELEVATIONS ONE
       TO"
      IF Q THEN LPRINT "YOUR DATA FILE SHOULD CONTAIN GEOPHONE
       ELEVATIONS ONE TO"
      PRINT "THE LINE.  THE FILE SHOULD BE IN ASCII FORMAT AND THE UNITS"
      IF Q THEN LPRINT "THE LINE.  THE FILE SHOULD BE IN ASCII FORMAT AND
       THE UNITS"
      PRINT "OF ELEVATION SHOULD CORRESPOND TO THE UNITS OF VELOCITY
       USED"
      IF Q THEN LPRINT "OF ELEVATION SHOULD CORRESPOND TO THE UNITS
       OF VELOCITY USED"
      PRINT : IF Q THEN LPRINT
      INPUT "ENTER THE NAME OF DATA FILE CONTAINING TIME-DISTANCE PAIRS    ",FILE$
      IF Q THEN LPRINT "ENTER THE NAME OF DATA FILE CONTAINING
       TIME-DISTANCE PAIRS?  ",FILE$
      OPEN FILE$ FOR INPUT AS #2
      IF Q THEN LPRINT "The following data is from external file: ";FILE$
      I=1
      WHILE NOT EOF(2)
      INPUT#2,Z(I)
      IF Q THEN LPRINT Z(I)
      I=I+1
      N=I-1
      WEND
      RETURN
930   ' subroutine to get data from keyboard
      N=1
950   LOCATE 18,5:PRINT SPACE$(50)
      LOCATE 19,5:PRINT SPACE$(50)
      LOCATE 6,22:PRINT SPACE$(10):LOCATE 6,10:INPUT "Input elevation ",Z(N)
      IF Q THEN LPRINT "Input elevation? ";Z(N)
      N=N+1
      LOCATE 18,5:COLOR 0,7:PRINT "To input another press <return>"
      LOCATE 19,5:PRINT"To return to main program press <Esc>.":COLOR 7,0
1020  K$=INKEY$:IF K$="" GOTO 1020
      IF K$=CHR$(13) GOTO 950
      IF K$=CHR$(27) THEN CLS:N=N-1:RETURN
      GOTO 1020
      END
```

PROGRAM 13F
PLUS-MINUS REFRACTION INTERPRETATION

This program calculates the depth to an irregular interface for shallow seismic refraction surveys. Engineering site investigations commonly require the depth to bedrock. Generally, the bedrock surface is overlain by weathered, residual soil, or dry and saturated alluvium. The bedrock surface is commonly irregular. Seismic refraction surveys can be used to investigate the bedrock surface. The "plus-minus" method is a quick and convenient method of interpretation. It is based on a wavefront approach.

The plus-minus technique used in the program is fully described in Cummings (Determination of depths to an irregular interface in shallow seismic refraction surveys using a pocket calculator, 1979, Geophysics, 44, 12, 1987-1998) and Hagadoorn (The plus-minus method of interpreting seismic refraction sections: Geophysical Prospecting, 7, 158-181). An example problem, its solution, and the program listing are below. V_1, V_2, V_3 Velocities of upper, middle, and lower media.

K, C Constants.

T_{A1-2} Arrival time of medium 2 refraction from shot A.

T_{B1-2} Arrival time of medium 2 refraction from shot B.

T_{AB1-2} Reciprocal time for medium 2 refractions.

T_A Arrival time of medium 3 refraction from shot A.

T_B Arrival time of medium 3 refraction from shot B.

T_{AB} Reciprocal time for medium 3 refractions.

THREE-LAYER CASE
(see Cummings, 1979)

V_1 = 900 ft/sec

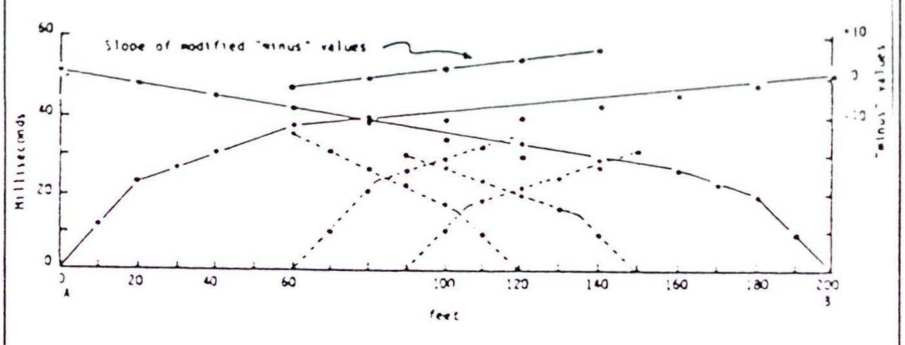
V_2 = 3000 ft/sec

V_3 = 8500 ft/sec

$T_{AB_{1-2}}$ = 42 msec (stations 80,100)

T_{AB_t} = 51 msec

STATIONS	A+80	+100	+120	+140	
$T_{A_{1-2}}$	27	32	27	34	msec
$T_{B_{1-2}}$	32	24	32	23	
T_{A_t}	38	39	41	43	
T_{B_t}	39	34	30	28	
K=1603.17,C=0.74815					
Depths to third layer:	21	18	12	14	ft



Example 1. Determine the depth to the third layer for the data given above. After Cummings and Ryland (MGHCP, 1981).

```
PROBLEM SOLUTION

SEG PROGRAM SEIS13F DETERMINATION OF DEPTH TO AN
                    IRREGULAR INTERFACE

For 2 layer case press 2
For 3 layer case press 3
3
V1,V2,V3 ? 900, 3000, 8500

All times must be entered in milliseconds.

Tabl_2 is the arrival time at the geophone farthest from
the shot point in a short seismic line not affected by 3rd layer
Tabl_2 ? 42

Tabt is the arrival time at the phone farthest from shotpoint
Tabt? 51

Station number ? 80
For station 80
 Tal-2,Tbl-2,Tat,Tbt ?  27 , 32 , 38 , 39
To do another, press <enter>
To get output, press <esc>
<ENTER>

Station number ? 100
For station 100
 Tal-2,Tbl-2,Tat,Tbt ?  32 , 24 , 39 , 34
To do another, press <enter>
To get output, press <esc>
<ENTER>

Station number ? 120
For station 120
 Tal-2,Tbl-2,Tat,Tbt ?  27 , 32 , 41 , 30
To do another, press <enter>
To get output, press <esc>
<ENTER>

Station number ? 140
For station 140
 Tal-2,Tbl-2,Tat,Tbt ?  34 , 23 , 43 , 28
To do another, press <enter>
To get output, press <esc>
<ESC>
                    STATION             DEPTH
                    80                   21.29257
                    100                  18.4781
                    120                  11.67355
                    140                  14.07234
 To return to system press any key
```

PROGRAM LISTING

```
'  DETERMINATION OF DEPTH TO AN IRREGULAR INTERFACE
'          IN SHALLOW SEISMIC REFRACTION SURVEYS
'
CLS
PRINT " DETERMINATION OF DEPTH TO AN
 IRREGULAR"
PRINT "                        INTERFACE USING SEISMIC REFRACTION"
PRINT
PRINT:INPUT "Hardcopy <Y/N>";A$:IF A$="Y" OR A$="y" THEN Q=1
PRINT:IF Q THEN LPRINT
IF Q THEN LPRINT "SEG PROGRAM SEIS13F DETERMINATION OF DEPTH TO
 AN"
IF Q THEN LPRINT "                        IRREGULAR INTERFACE"
IF Q THEN LPRINT
DIM NME$(200),Z(200)
'************ write opening screen ***************
CLS
LOCATE 5,35:COLOR 0,7:PRINT " SEIS-13F ":COLOR 7,0
LOCATE 7,20:PRINT "Determination of Depth to an Irregular"
LOCATE 8,20:PRINT "Interface in shallow refraction surveys"
LOCATE 10,15:PRINT "Based on Calculator program by Cummings & Ryland"
LOCATE 12,15:PRINT "BASIC program by Doug Dodge"
LOCATE 15,10:PRINT "For 2 layer case press 2"
IF Q THEN LPRINT "For 2 layer case press 2"
LOCATE 16,10:PRINT "For 3 layer case press 3"
IF Q THEN LPRINT "For 3 layer case press 3"
340  K$=INKEY$:IF K$="" GOTO 340
IF Q THEN LPRINT K$
IF K$="2" GOTO 410
IF K$="3" GOTO 670
GOTO 340
'*******************************************
'process 2 layer case here
410  N=1
CLS:LOCATE 10,30:INPUT "Enter V1,V2 ",V1,V2:CLS
IF Q THEN LPRINT:LPRINT " V1,V2 ? ",V1,V2
K=.5*V1/SQR(1-V1*V1/V2/V2)
LOCATE 10,30:PRINT "Enter all times in milliseconds"
IF Q THEN LPRINT "Enter all times in milliseconds"
LOCATE 15,20:INPUT "Enter reciprocal time tab ",TAB:TAB=TAB/1000!
IF Q THEN LPRINT "Reciprocal time (Tab) ? ",TAB*1000
490  CLS:LOCATE 15,20:INPUT "Enter the station number ",NME$(N):CLS
IF Q THEN LPRINT "Station number ? ",NME$(N)
LOCATE 15,20:PRINT "For station ",NME$(N):INPUT "Input ta and tb ",TA,TB
IF Q THEN LPRINT "For station ",NME$(N):LPRINT " Ta and Tb ";TA","TB
TA=TA/1000!:TB=TB/1000!
Z(N)=K*(TA+TB-TAB)
N=N+1
LOCATE 20,20:PRINT "To do another, press <enter>"
IF Q THEN LPRINT "To do another, press <enter>"
LOCATE 21,20:PRINT "To get output, press <esc>"
IF Q THEN LPRINT "To get output, press <esc>"
600  K$=INKEY$:IF K$ ="" GOTO 600
IF Q THEN LPRINT K$
IF K$=CHR$(13) GOTO 490
IF K$=CHR$(27) THEN GOSUB 1070:END
'*****************************************
'
'process 3 layer case here
670  N=1:CLS
LOCATE 10,20:INPUT "Enter V1,V2,V3 ",V1,V2,V3:CLS
IF Q THEN LPRINT " V1,V2,V3 ? ",V1,V2,V3
K=.5*V2/SQR(1-V2*V2/V3/V3)
C=(SQR(1/V1/V1-1/V3/V3)-SQR(1/V2/V2-1/V3/V3))/SQR(1/V1/V1-1/V2/V2)
PRINT:PRINT:PRINT:IF Q THEN LPRINT
PRINT "All times must be entered in milliseconds"
IF Q THEN LPRINT "All times must be entered in milliseconds"
```

```
      PRINT:PRINT:PRINT:IF Q THEN LPRINT
      PRINT"Tab1_2 is the arrival time at the geophone farthest from"
      IF Q THEN LPRINT"Tab1_2 is the arrival time at the geophone farthest from"
      PRINT"the shot point in a short seismic line not affected by 3rd layer"
      IF Q THEN LPRINT"the shot point in a short
                                  seismic line not affected by 3rd layer"
      PRINT:PRINT:PRINT:IF Q THEN LPRINT
      INPUT "Enter Tab1_2 ",TAB12:TAB12=TAB12/1000!:CLS
      IF Q THEN LPRINT " Tab1_2 ? ",TAB12*1000
      LOCATE 12,20: PRINT"Tabt is the arrival time
                                          at the phone farthest from shotpoint"
      IF Q THEN LPRINT "Tabt is the arrival
                                     time at the phone farthest from shotpoint"
      LOCATE 15,20:INPUT "Enter Tabt ",TABT:TABT=TABT/1000!
      IF Q THEN LPRINT " Tabt ? ",TABT*1000
860   CLS :IF Q THEN LPRINT
      LOCATE 15,20:INPUT "Enter a station number ",NME$(N):CLS
      IF Q THEN LPRINT "Station number ? ";NME$(N)
      LOCATE 15,20:PRINT "For station ",NME$(N)
      IF Q THEN LPRINT "For station ";NME$(N)
      LOCATE 17,20:INPUT "Enter Ta1-2,Tb1-2,Tat,Tbt ",TA12,TB12,TAT,TBT
      IF Q THEN LPRINT " Ta1-2,Tb1-2,Tat,Tbt ? ";TA12","TB12","TAT","TBT
      TA12=TA12/1000!:TB12=TB12/1000!:TAT=TAT/1000!:TBT=TBT/1000!
      D=C*(TA12+TB12-TAB12)
      Z(N)=K*((TAT+TBT-TABT)-D)
      N=N+1
      LOCATE 20,20:PRINT "To do another, press <enter>"
      IF Q THEN LPRINT "To do another, press <enter>"
      LOCATE 21,20:PRINT "To get output, press <esc>"
      IF Q THEN LPRINT "To get output, press <esc>"
      IF Q THEN LPRINT K$
1020  K$=INKEY$:IF K$ ="" GOTO 1020
      IF K$=CHR$(13) GOTO 860
      IF K$=CHR$(27) THEN GOSUB 1070:END
      '****************************************
      '
1070  'subroutine to output results
      CLS:IF Q THEN LPRINT
      PRINT TAB(20) "STATION" TAB(40) "DEPTH"
      IF Q THEN LPRINT TAB(20) "STATION" TAB(40) "DEPTH"
      PRINT:IF Q THEN LPRINT
      FOR J=1 TO N-1
      PRINT TAB(20) NME$(J) TAB(40) Z(J)
      IF Q THEN LPRINT TAB(20) NME$(J) TAB(40) Z(J)
      NEXT J
      LOCATE 22,10:COLOR 0,7:PRINT " To return to system press any key "
      :COLOR 7,0
      IF Q THEN LPRINT " To return to system press any key ":COLOR 7,0
1180  K$=INKEY$:IF K$="" GOTO 1180
      CLS:END
```

PROGRAM SEIS13G
CALCULATION OF THICKNESS OF HIDDEN LAYER
WITH VELOCITY INVERSION
SHALLOW SEISMIC REFRACTION SURVEYS

Geologic conditions exist in which where velocity inversions produce hidden layers with respect to seismic refraction surveys. Program SEIS13G describes the special case where a layer has a lower velocity than the layer above it and a higher velocity than the layer below. The lowermost layer must have the highest velocity of the three. Because the low-velocity layer refracts the seismic wave toward the normal, a head wave is not generated at the upper surface of the low-velocity layer. The head wave from the third layer will nonetheless exist. Consequently, the existence of the low-velocity layer is not apparent on a refraction record. However, under certain circumstances, its presence may be identified by time delays on a refraction record between the slopes for the underlying and overlying layers.

The significance for identifying the low-velocity layer in engineering geophysics is that it may represent, for example, a bentonitic layer sandwiched between an overlying sandstone and an underlying limestone. The bentonite may be a potential slip plane in a landslide.

Two major errors are introduced in interpreting the time-distance graph when a low-velocity hidden layer exists. The first is the non-detection of the layer because it does not show on a time-distance curve. The second is the incorrect interpretation of the depth to the interface underlying the low-velocity layer. The data from the time-distance graph would result in a depth deeper than the true depth. An illustration of the problem is given in Figure 1.

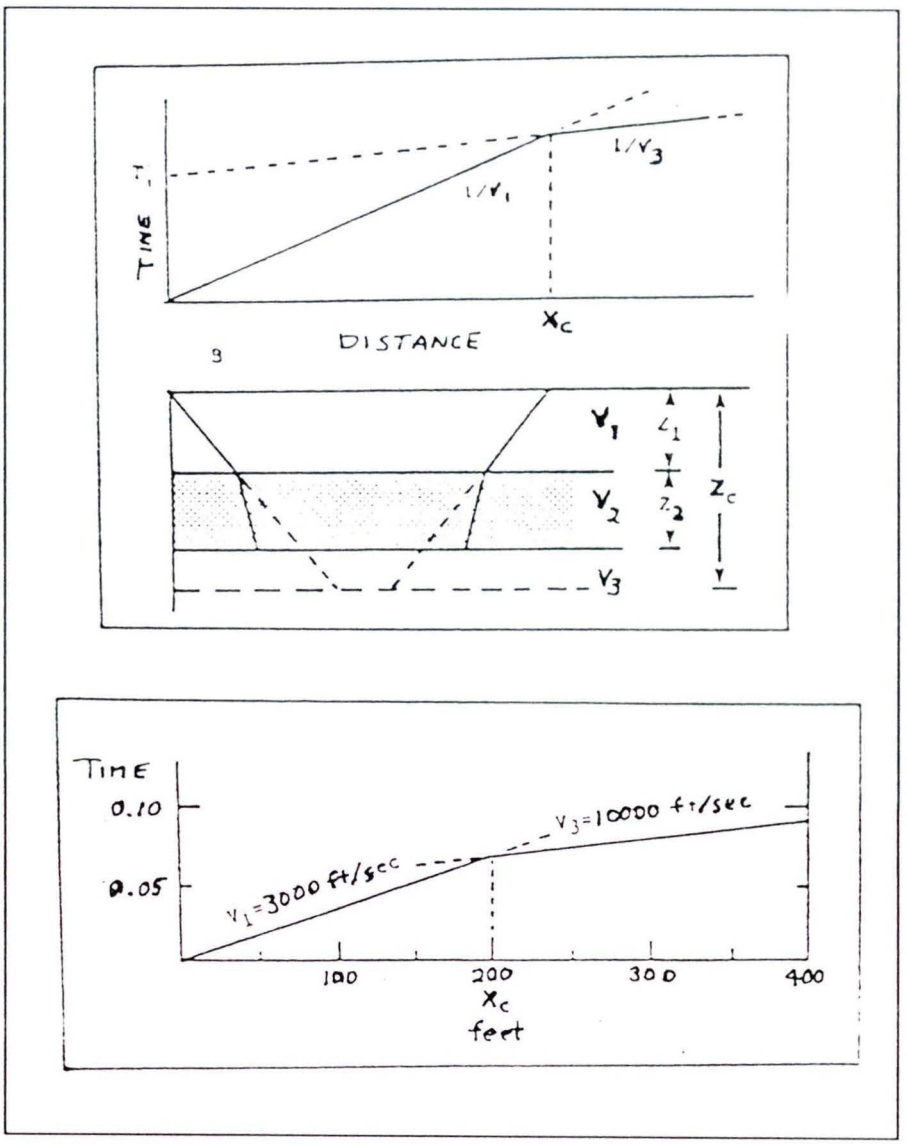


Figure 1. A low velocity layer and its effect on a refraction time-distance curve. After Cummings (MGHCP, 1981).

Program SEIS13G calculates the thickness of a low-velocity layer of a given velocity assuming that it is present. For a discussion of the method used, see Mooney (Handbook of Engineering Geophysics, 1977, Bison Instruments, Inc., Minneapolis, Minn.). Program SEIS13G and this documentation are modified from David Cummings (MGHCP, 1981). An example problem, its solution, and the program listing follow.

Example 1. Determine a range of values for the depth to the third layer by assuming reasonable values for the velocity of the low-velocity layer and upper layer thickness for the following model: V1 = 3000 ft/s, V3 = 10000 ft/s, and XC = 200 ft. After Cummings (MGHCP, 1981).

```
PROBLEM SOLUTION
SEG PROGRAM SEIS13G  CALCULATION FOR THICKNESS OF HIDDEN LAYER
 V1,V3 ?  3000 , 10000
Input crossover distance ?   200
```

Assumed Velocity	Assumed thickness of layer 1								
	7.33	14.6	22.0	29.3	36.6	44.0	51.3	58.7	66.0
0300	6.30	5.60	4.90	4.20	3.50	2.80	2.10	1.40	.700
0600	12.6	11.2	9.81	8.41	7.01	5.61	4.20	2.80	1.40
0900	18.9	16.8	14.7	12.6	10.5	8.43	6.32	4.21	2.10
1200	25.3	22.5	19.7	16.9	14.1	11.2	8.46	5.64	2.82
1500	31.8	28.3	24.7	21.2	17.7	14.1	10.6	7.08	3.54
1800	38.4	34.1	29.8	25.6	21.3	17.0	12.8	8.53	4.26
2100	45.1	40.0	35.0	30.0	25.0	20.0	15.0	10.0	5.01
2400	51.9	46.1	40.3	34.6	28.8	23.0	17.3	11.5	5.76
2700	58.8	52.3	45.8	39.2	32.7	26.1	19.6	13.0	6.54
3000	66.0	58.7	51.3	44.0	36.6	29.3	22.0	14.6	7.33

Each entry in the above array is the hidden layer thickness
corresponding to the assumed velocity and layer 1 thickness

PROGRAM LISTING

```
'SEIS13G CALCULATION OF THE THICKNESS OF HIDDEN LAYER WITH
 VELOCITY
'     INVERSION, SHALLOW SEISMIC REFRACTION SURVEYS
CLS
TITLE$="SEG PROGRAM SEIS13G CALCULATION FOR THICKNESS OF
 HIDDEN LAYER"
PRINT:PRINT TITLE$
PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN QQ=1
PRINT:IF QQ THEN LPRINT TITLE$ :LPRINT
'*********** write opening screen ***************
CLS:IF QQ THEN LPRINT
LOCATE 4,30:COLOR 0,7:PRINT " SEIS-13G ":COLOR 7,0
LOCATE 7,20:PRINT "Calculation of Thickness of Hidden Layer"
LOCATE 8,20:PRINT "in Shallow Seismic Refraction Surveys"
LOCATE 10,20:PRINT "based on calculator program by David Cummings"
LOCATE 11,20:PRINT "BASIC program by Doug Dodge"
LOCATE 15,20:PRINT "To continue press any key"
250 K$=INKEY$:IF K$="" GOTO 250
'************************************************
CLS:IF QQ THEN LPRINT
INPUT "Input V1,V3 ",V1,V3
IF QQ THEN LPRINT " V1,V3 ? ";V1","V3
INPUT "Input crossover distance ",XC
IF QQ THEN LPRINT "Input crossover distance ? ",XC
CLS:IF QQ THEN LPRINT
ZC=XC/2*SQR((V3-V1)/(V3+V1)):'establish upper limit for layer 1
'*********** write the working screen *************
FOR I=1 TO 10
V2=V1/10*I
LOCATE 5,1:PRINT " Assumed"
LOCATE 6,1:PRINT "Velocity"
FOR K=1 TO 15:LOCATE K+4,10:PRINT "¦":NEXT
LOCATE 6,10:PRINT "¦":FOR K=1 TO 55:LOCATE 6,K+10:PRINT "-":NEXT
LOCATE 3,20:PRINT " Assumed thickness of layer 1 "
'*********************************************************
'
FOR K=1 TO 9:NUM$=STR$(ZC/10*K):OT$=LEFT$(NUM$,5):LOCATE
        5,6*K+5:PRINT OT$:NEXT
Q=SQR(((V3/V1)^2-1)/((V3/V2)^2-1))
A=Q*XC/2*SQR((V3-V1)/(V3+V1))
VL$=LEFT$(STR$(V2),5):LOCATE I+7,2:PRINT VL$:' print the test v2 values
'
' for each of 9 test thicknesses of layer one calculate the layer 2 thickness
FOR J=1 TO 9
Z1=ZC/10*J
LAYER=A-Z1*Q
NUM$=STR$(LAYER):OT$=LEFT$(NUM$,5)
LOCATE I+7,6*J+5:PRINT OT$
NEXT:NEXT
LOCATE 20,20:PRINT "Each entry in the above array is the hidden layer thickness"
LOCATE 21,20:PRINT "corresponding to the assumed velocity and layer 1 thickness"
LOCATE 22,10:COLOR 0,7:PRINT " Press any key to return to system ":COLOR 7,0
FOR ROW=1 TO 24
FOR COL=1 TO 78
IF QQ THEN LPRINT CHR$(SCREEN(ROW,COL));
NEXT COL
IF QQ THEN LPRINT CHR$(SCREEN(ROW,COL))
NEXT ROW
650 K$=INKEY$:IF K$="" GOTO 650
CLS:END
```

PROGRAM SEIS13H
DETERMINATION OF MAXIMUM THICKNESS OF BLIND ZONE IN SHALLOW SEISMIC REFRACTION SURVEYS

This program determines the maximum thickness of the blind zone for sites at which the layer velocity increases with depth from layer to layer. See the previous program for sites at which a low velocity layer occurs.

The time-distance graph is the basis of refraction interpretation. However, subsurface layers are not always recorded as first arrivals on time-distance graphs. The most famous example of this phenomenon is a low-velocity layer. However, a subsurface layer may also fail to show up as a first arrival if the critical distance for an underlying layer is less. In this situation, the head wave from the deeper layer arrives at the geophone earlier than the arrivals from the undetected layer. The blind zone refers to the maximum thickness of the undetected layer. The hidden layer refers to its thickness between zero and maximum. For program SEIS13H, the velocity of the undetected layer is assumed to be higher than the overlying layer but lower than the underlying layer. Thus, the usual assumption of increasing layer velocity with depth is maintained from layer to layer.

The hidden layer problem is important in engineering geophysics. The hidden layer may be a saturated zone or a potential slip plane for a landslide. Two major errors can occur in refraction interpretation when a hidden layer exists. Without additional site information, only layers that appear as first arrivals will be detected. Secondly, the depth to the interface below the undetected layer will be underestimated. Fortunately, the presence of hidden layers can be recognized from lithologic cutting and cores, from downhole and crosshole seismic surveys, from geophysical well logs, from

seismic reflection surveys, or possibly from second arrivals on refraction records.

This program computes the maximum possible thickness of a hidden layer (IE the blind zone) at a site given the observed crossover distance, the observed intercept time, the velocity of the substratum, and the velocity and thickness of the overlying layer. The equations are from Hawkins and Maggs (Nomograms for determining maximum errors and limiting conditions in a seismic refraction survey with a blind zone problem, 1961, Geophysical Prospecting, 9, 526-532). Figure 1 shows an illustration of the blind zone phenomenon. An example problem, its solution, and the program listing follow.

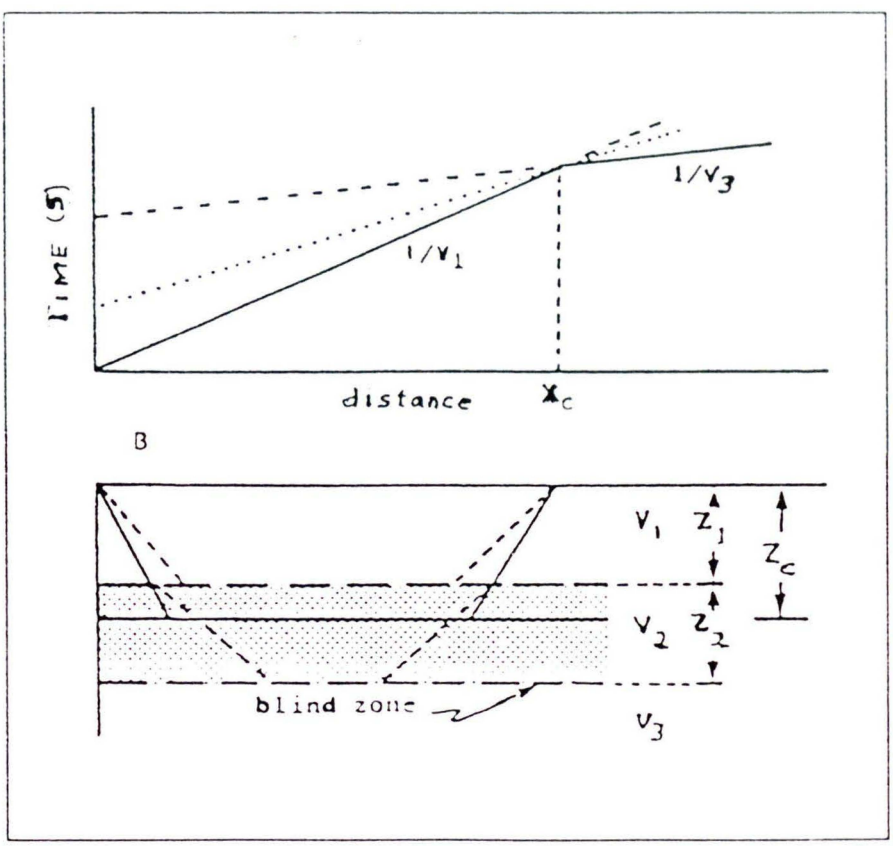
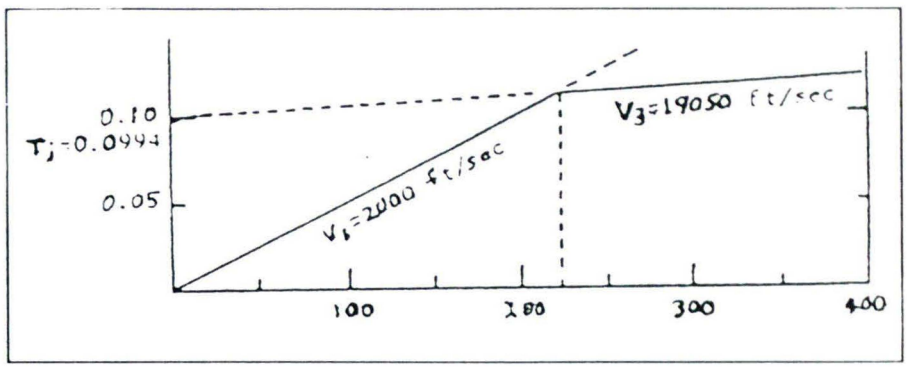


Figure 1. The schematic geologic cross-section and time-distance graph that might result in a blind zone situation. After Cummings (MGHCP, 1981).



Example 1. Determine the maximum thickness of the blind zone for a range of assumed hidden layer velocities using parameters from the time-distance graph shown above. After Cummings (MGHCP, 1981).

PROBLEM SOLUTION

```
SEIS-13H
Calculation of Thickness of Hidden Layer
in Shallow Seismic Refraction Surveys
V1,V3 ?   2000, 19050  Crossover distance ?  222
Intercept time in milliseconds ?  99.4
```

Assumed velocity layer 2	Depth to top of blind layer	Thickness of blind layer	Depth for recorded refractor
04273	66.8	72.2	139.1
05410	75.3	69.2	144.5
06546	81.0	65.8	146.8
07683	85.0	62.3	147.3
08820	88.1	58.5	146.6
09956	90.5	54.6	145.2
11093	92.5	50.5	143.0
12230	94.1	46.3	140.4
13366	95.5	41.8	137.3
14503	96.6	37.1	133.7
15640	97.6	31.9	129.6
16776	98.5	26.1	124.6
17913	99.2	19.0	118.2

```
press any key to return to system
```

PROGRAM LISTING

```
    'SEIS13H  MAXIMUM THICKNESS OF BLIND ZONE
    CLS:PRINT "SEIS13H  MAXIMUM THICKNESS OF BLIND ZONE"
    PRINT:INPUT "Hardcopy <Y/N> ";A$:IF A$="Y" OR A$="y" THEN Q=1
    '*********** write opening screen ***************
    CLS
    LOCATE 4,30:COLOR 0,7:PRINT " SEIS-13H ":COLOR 7,0
    IF Q THEN LPRINT " SEIS-13H "
    LOCATE 7,20:PRINT "Calculation of Thickness of Hidden Layer"
    IF Q THEN LPRINT "Calculation of Thickness of Hidden Layer"
    LOCATE 8,20:PRINT "in Shallow Seismic Refraction Surveys"
    IF Q THEN LPRINT "in Shallow Seismic Refraction Surveys"
    LOCATE 10,20:PRINT "based on calculator program by David Cummings"
    LOCATE 11,20:PRINT "BASIC program by Doug Dodge"
    LOCATE 15,20:PRINT "To continue press any key"
240 K$=INKEY$:IF K$="" GOTO 240
    '************************************************
    CLS
    INPUT "Input V1,V3 ",V1,V3
    IF Q THEN LPRINT "V1,V3 ? ",V1,V3
    INPUT "Input crossover distance ",XC
    IF Q THEN LPRINT "Crossover distance ? ",XC
    INPUT "Input intercept time in milliseconds ",TI:TI=TI/1000!
    IF Q THEN LPRINT "Intercept time in milliseconds ? ";TI*1000
    CLS:IF Q THEN LPRINT
    '*********** write the working screen *************
    LOCATE 2,1:PRINT " Assumed              Depth to   Thickness  Depth for"
    LOCATE 3,1:PRINT "velocity               top of     of blind   recorded "
    LOCATE 4,1:PRINT "layer 2              blind layer   layer    refractor"
    FOR K=1 TO 17:LOCATE K+1,10:PRINT "¦":NEXT
    FOR I=1 TO 9:LOCATE 5,I:PRINT "-"      :NEXT
    LOCATE 5,10:PRINT "¦":FOR J=1 TO 45:LOCATE 5,J+10:PRINT "-"      :NEXT
    SLOPE=(V3-V1)/15
    FORM$= "           ####.#      ####.#      ####.#"
    FOR K=2 TO 14
    V2=V1+SLOPE*K
    VL$=LEFT$(STR$(V2),6):LOCATE K+4,2:PRINT VL$:' print the test v2 values
    GOSUB 580
    LOCATE K+4,12:PRINT USING FORM$;Z1,Z2, DEPTH
    NEXT
    LOCATE 22,10:COLOR 0,7
    :PRINT " press any key to return to system ":COLOR 7,0
    FOR ROW=1 TO 24:FOR COL=1 TO 78
    IF Q THEN LPRINT CHR$(SCREEN(ROW,COL));
    NEXT COL:IF Q THEN LPRINT CHR$(SCREEN(ROW,79))
    NEXT ROW
540 K$=INKEY$:IF K$="" GOTO 540
    CLS:END
    '
    'sub to do the work of the program
580 ZC=TI/2*V1*V3/SQR(V3^2-V1^2)
    Z1=XC/2*SQR((V2-V1)/(V2+V1))
    Z2=(TI/2-Z1*SQR((V3^2-V1^2))/(V1*V3))*V2*V3/SQR(V3^2-V2^2)
    DEPTH=Z1+Z2
    RETURN
    END
```

PROGRAM SEIS13I
REFRACTION INTERPRETATION
USING BEST-FIT INTERCEPTS

This program interprets refraction results for the case of a single horizontal layer over a half-space. The program finds the optimum critical distance, intercept time, and velocities by fitting best-fit lines in a least- squares sense to the time-distance data., The thickness of the top layer is then calculated and statistical evaluation of the results performed. Input data is read from a file of distance time pairs with the value separated by commas.

EXAMPLE PROBLEM: Interpret the following refraction data assuming a single horizontal layer over a half-space.

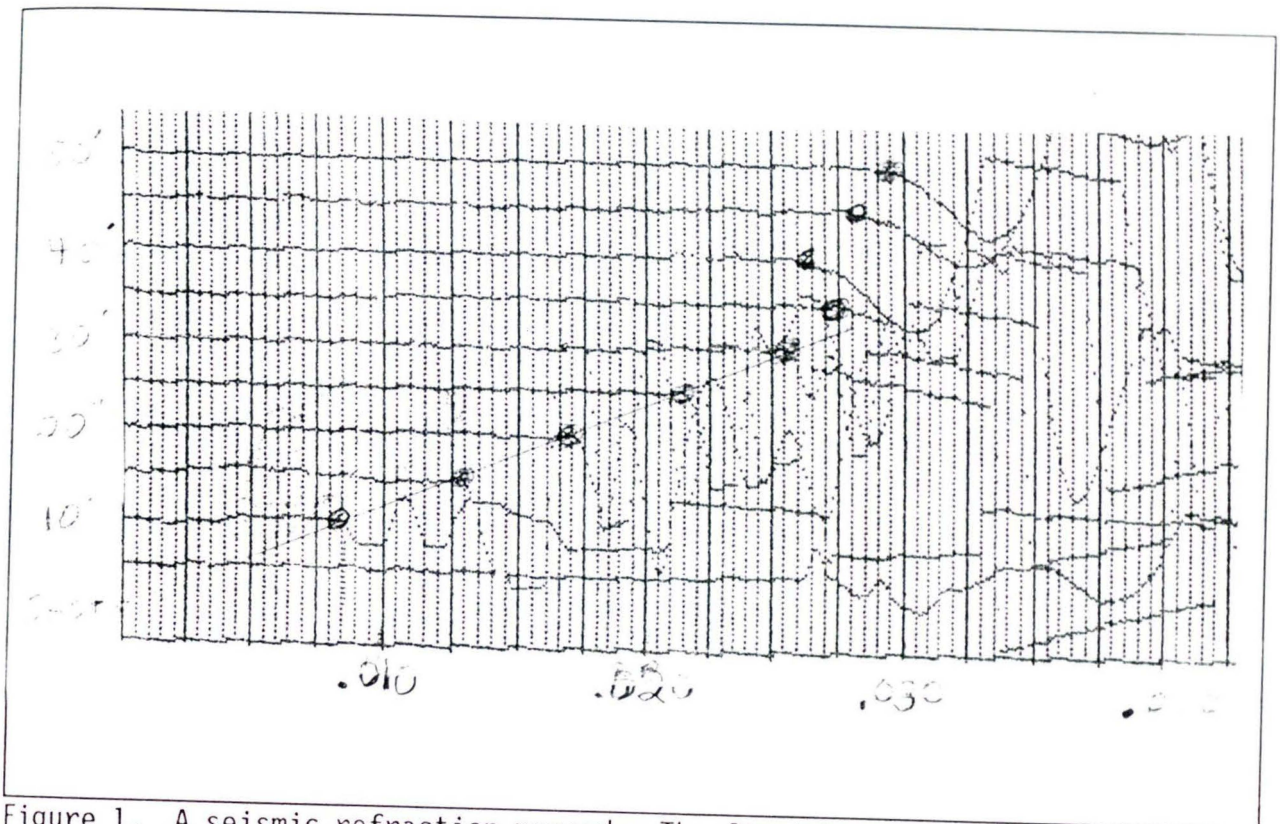


Figure 1. A seismic refraction record. The first breaks are tabulated on the next page.

Distance from Shot (ft)	Arrival Time (s)
10	.0085
15	.0130
20	.017
25	.022
30	.026
35	.0275
40	.026
45	.028
50	.029

PROBLEM SOLUTION:

```
Name of Input data file with distance-time pairs? SEIS13I.DAT
Number of distance-time pairs? 9
Name of file for best fit line plot (Must be .dat)? OUT.DAT

REFRACTION RESULTS

The critical distance is 30
The intercept time is 0.0221 s +/- 13%

Velocity of top layer:    1153 +/- 1%
Velocity of the halfspace: 7692 +/- 55%

The thickness of the top layer is 12 +/- 15%
```

PROGRAM LISTING

```
                    PROGRAM SEIS13I
                REFRACTION INTERPRETATION
                USING BEST-FIT INTERCEPTS


'version 1.0                University of Idaho
'                              Moscow, Idaho
'Refraction
'Interpretation
'
'SEIS13I is a BASIC program to interpret refraction results for the
'case of a single horizontal layer over a half-space. The program
'finds the optimum critical distance, intercept time and velocities
'by fitting best fit lines to the time-distance data. The thickness
'of the top layer is then calculated and statistical evaluation of the
'results performed. Input data is read from a file of distance-time pairs.
'
'-----------------------------------------------------------------------
'
'                              Method
'
'   The thickness Z of the top layer in terms of the intercept time Ti,
'   velocities V1 and V2 is:
'
'                         Ti          V1 V2
'                  Z = ----  -----------------------
'                       2    SQR ( V2 V2 - V1 V1 )
```

```
'
'  Ti is found from the intercept of the best fit line through the
'  head wave arrivals with the time axis.
'
'  V1 and V2 are found from the inverse slopes of the best fit lines
'  to the direct and head wave first arrivals.
'
'  To separate the arrivals into
'  direct and head waves, the optimal critical distance
'  is determined by trying all possible two line fits to the data.
'
'  The optimum critical distance is chosen to be the one
'  for which the two line fit has minimum estimation variance.
'
'-----------------------------------------------------------------------
'
'                     Initialize Variables
'
DIM TIME(100),DISTANCE(100)       'Arrival time, shot-receiver distance
'                                  ' maximum array size.
DIM X(100),Y(100)                 'Work space for best fit routines.
I=0:J=0 :IP=0                      'Counters for FOR-NEXT loops
NP=0                              'Number of data points to be entered
NDIR=0:NHEAD=0                    'Number of direct and head wave
                                  ' arrivals  respectively.
VAR1=0                            'Variance of direct arrivals from
'                                 ' best fit line.
VAR2=0                            'Variance of head wave arrivals.
ESTVAR=0                          'Variance of all arrivals from two-line
'                                    best fit.
V1=0                              'Velocity of top layer.
V2=0                              'Velocity of half-space.
TI=0                              'Intercept time
PEV1=0:PEV2=0                     'Percent errors of velocities
PETI=0                            'Percent error of intercept time
Z=0:PEZ=0                         'Thickness of top layer and its %E.
SLOPE1=0:SLOPE2=0                 'Slopes of direct and head arrivals.
MIN=99999!                         'Minimum value of estimation variance.
'
A=0:B=0:VAR=0:SA=0:SB=0           'These are all arguments returned from
'                                 ' the least squares subroutine:
'                                 ' A is slope; B is intercept; SA and SB
'                                 ' are the standard errors of the slope
'                                 ' and intercept. VAR is estimation
'                                 ' variance.
'-----------------------------------------------------------------------
'
'                          MAIN PROGRAM
'
GOSUB 2500                              'Data entry.
'
GOSUB 2900                               'Find best two-line fit to the
'                                       ' time-distance data and
'                                       ' relevent statistics.
'
GOSUB 6000                              'Calculate depth.
GOSUB 7000                              'Calculate standard error of depth.
GOSUB 7500                              'Print out results.
'
END                                     'End of main program.
'-----------------------------------------------------------------------
'
'                           SUBROUTINES
'
'-----------------------------------------------------------------------
'                            DATA ENTRY
'
02500 NP=0
INPUT "Name of Input data file with distance-time pairs"; FILE$
```

```
OPEN FILE$ FOR INPUT AS #1
INPUT "NUMBER OF DISTANCE-TIME PAIRS";NP
'
FOR I=1 TO NP                'Read data pairs:
'
 INPUT #1,DISTANCE(I),TIME(I)
PRINT DISTANCE(I),TIME(I)
'
NEXT I                              ' from remaining DATA statements.
'
CLOSE #1
RETURN                              'Return to main program.
'-------------------------------------------------------------------
'                   FIND OPTIMUM CRITICAL DISTANCE
'
02900 NP2=NP-2                           'Need at least two points in head
'                                   ' wave arrival. One in direct.
FOR IP=1 TO NP2                     'Try every possible way of separating
'                                   ' the arrivals into direct and head
'                                   ' types.
   NDIR=IP :NHEAD=NP-IP              'Calculate number of direct and head
'                                   ' arrivals in this particular try.
'
   FOR J=1 TO NDIR                  'Take this assumed set of direct wave
      X(J)=DISTANCE(J)              ' arrivals, find the best fit line
      Y(J)=TIME(J)                  ' constrained to go through the
   NEXT J                           ' origin, and calculate its variance.
   N=NDIR
   GOSUB 8500                       'Best fit line through origin.
   A1=A                             'Save the slope as A1.
   VAR1=VAR                         'Save variance as VAR1.
   SA1=SA                           'Save standard error of slope as SA1.
   FOR J=1 TO NHEAD                 'Take the assumed set of head waves.
      X(J)=DISTANCE(J+NDIR)         ' find the best fit line, and
      Y(J)=TIME(J+NDIR)             ' calculate its variance.
   NEXT J
   N=NHEAD
   GOSUB 9000                       'Finds best fit line.
'
   ESTVAR=(NHEAD*VAR+NDIR*VAR1)/NP
'
PRINT IP,ESTVAR
'                                   'Find the estimation variance for the
'                                   ' two-line fit using a weighted
'                                   ' average of the direct and head wave
'                                   ' arrival variances.
'
   IF (ESTVAR>MIN) THEN 3500        'Check if this value less than any
     MIN=ESTVAR                     '  previous. If so, find:
     TI=B                           'Best fit intercept time.
     XC=TI/(A1-A)                  'Best fit critical distance.
     V1=1/A1                        'Best fit top layer velocity.
     V2=1/A                         'Best fit half space velocity.
     PETI=SB*100/TI                 'Percent error of intercept time.
     PEV1=SA1/A1*100                'Approx. % error of V1.
     PEV2=SA/A*100                  'Approx. % error of V2.
03500 NEXT IP                              '
'
RETURN                              'Return to main program.
'-------------------------------------------------------------------
'
'                CALCULATE TOP LAYER THICKNESS
'
06000 Z=.5*TI*V1*V2/SQR(V2*V2-V1*V1)  'Find thickness of top layer. 6100 '
RETURN
'-------------------------------------------------------------------
'
'                CALCULATE % ERROR OF THICKNESS
'
```

```
07000 PEZ=PETI+PEV1+PETI*PEV1/100       'The experimental error in Z is mostly
                                        'dependent on the errors in TI and V1.
'
'
RETURN
'-------------------------------------------------------------------------
07500 '                          PRINT OUT RESULTS
'
INPUT "Name of file for best fit line plot (Must be .dat)";PFILE$
OPEN PFILE$ FOR OUTPUT AS #2
PRINT#2,0,0
PRINT#2,XC,(XC/V1)
PRINT#2,DISTANCE(NP),(TI+DISTANCE(NP)/V2)
CLOSE#2
PRINT:PRINT:PRINT:PRINT
PRINT "REFRACTION RESULTS"
PRINT
PRINT "The critical distance is ";XC;
PRINT "The intercept time is ";TI;" s  +/- ";INT(PETI);" %"
PRINT
PRINT "Velocity of the top layer:";INT(V1);" +/- ";INT(PEV1);" % "
PRINT "Velocity of the halfspace:";INT(V2);" +/- ";INT(PEV2);" %"
PRINT
PRINT "The thickness of the top layer is";INT(Z);" +/- ";INT(PEZ); " %"
'
RETURN                                  'to end of main program
'-------------------------------------------------------------------------
'
'               FIND BEST FIT LINE THROUGH THE ORIGIN
'
' This subroutine fits a best fit line through the origin
' to N data points X(1),Y(1)  X(2),Y(2).....X(N),Y(N). The best fit
' slope is A. The estimation variance of the fit is VAR. The standard
' error of the slope is SA.
'
'
'              sum (xy)                          sum (yy) - A sum (xy)
'         A = --------                    VAR = ---------------------
'              sum (xx)                                  N
'
'
'                                  N  VAR
'              SA = SQR (-----------------------------)
'                         N sum (xx) - sum (x) sum (x)
'
'Global arguments from calling program:
'
' N                                 'Number of data points
' X(N)                              'Array of N x coords
' Y(N)                              'Array of N y coords
'DIM X(N), Y(N)                     'DIM statement with explicit value
'                                   ' for N must appear in calling program.
'Initialize variables
'
08500 SUMX=0:SUMY=0                       'Sum of x, y coords
SUMXX=0:SUMYY=0:SUMXY=0             'Sums of squares and cross products.
VAR=0                               'Estimation Variance
SA=0                                'Standard error of slope.
A=0                                 'Best fit slope through origin.
'
'CALCULATION OF SUMS
'
FOR I=1  TO N
   SUMX=SUMX+X(I)
   SUMY=SUMY+Y(I)
   SUMXY=SUMXY+X(I)*Y(I)
   SUMXX=SUMXX+X(I)*X(I)
   SUMYY=SUMYY+Y(I)*Y(I)
NEXT I
'
```

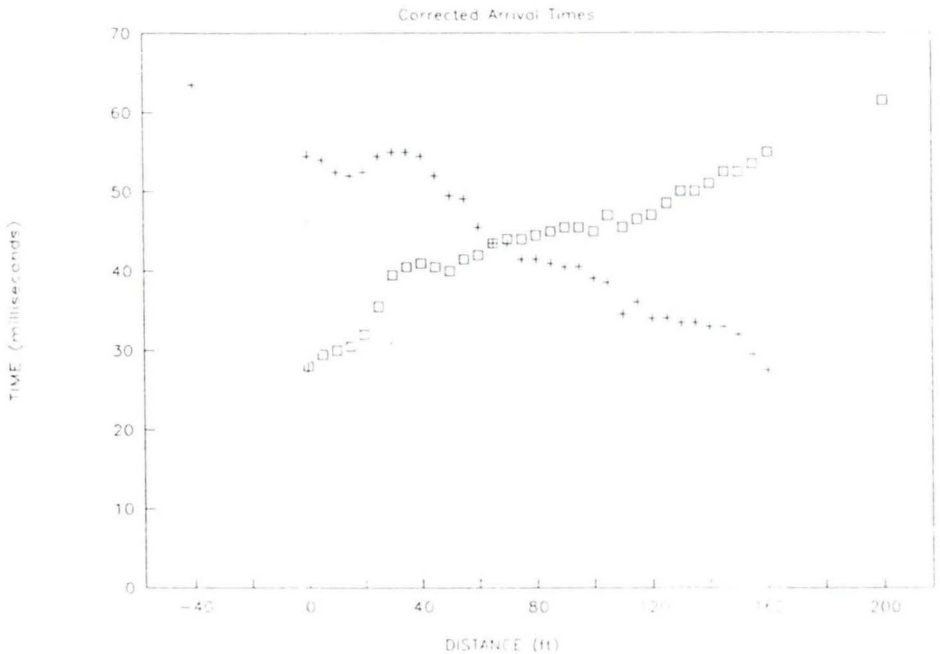
```
'Calculations of slope, variance, and standard error.
'
A = SUMXY/SUMXX                        'Best fit slope
IF N=1 THEN 8720                       'Perfect fit; variance is zero.
VAR = (SUMYY-A*SUMXY)/N                'Estimation variance
IF VAR<0 THEN VAR=0                     'In case of round off errors.
SA=SQR(N*VAR/(N*SUMXX-SUMX*SUMX))
'                                      'Standard error of slope
'
08720 RETURN                                 'to calling program.
'-------------------------------------------------------------------------
09000 'LSTSQ1    vers. 1            KF Sprenke                  Nov 20, 1985
'                              University of Idaho
'                                 Moscow, Idaho
'                               (208) 885-7977
'
'
'LSTSQ1 is a subroutine for the fitting of a best fit straight line in
'a least square sense to N data points X(1),Y(1)  X(2),Y(2)  X(3),Y(3)
'.....X(N),Y(N).
'The best fit slope is A, the best fit y-intercept is B.
'
'
'                    **FORMULAS**
'
'The normal equations solved for slope A and y-intercept B are:
'
'             N sum (xy) - sum (x) sum (y)
'      A =    ----------------------------
'             sum (x) sum (x) - N sum (xx)
'
'
'            sum (xx) sum (y) - sum (x) sum (y)
'      B =   ----------------------------------
'               sum (x) sum (x)  - N sum (xx)
'
'Further useful statistics include VAR, the variance of the estimate,
'from which the standard error of the slope SA and the standard error of
'the y-intercept SB may be calculated.
'
'             sum (yy) - B sum (y) - A sum (xy)
'      VAR =  ---------------------------------
'                            N
'
'
'                       VAR  N
'      SA =  SQR (--------------------------  )
'                 N sum (xx) - sum (x) sum (x)
'
'
'                      sum (xx)
'      SB =  SA  SQR (----------)
'                        N
'
'
'
'
'GLOBAL ARGUMENTS FROM CALLING PROGRAM
'
'
' N                                     'Number of data points
' X(N)                                  'Array of N x coordinates
' Y(N)                                  'Array of N y coordinates
'
' DIM X(N),Y(N)                         'DIM statement must appear in calling
'                                       'program with explicit value for N.
'
'
```

```
' INITIALIZE VARIABLES
'
SUMX=0:SUMY=0                          'Sum of x; sum of y coordinates.
SUMXX=0:SUMYY=0:SUMXY=0                'Sum of cross products
VAR=0                                  'Variance of estimate
SA=0                                   'Standard error of slope
SLOPE=0                                'Best fit slope
A=SLOPE                                'Abbreviation for slope in equations
INTERCEPT=0                            'Best fit Y-intercept
B=INTERCEPT                            'Abbreviation for intercept
SB=0                                   'Standard error of intercept
I=0                                    'Counter in FOR/NEXT LOOP
'
'
'
'
FOR I=1 TO N                           'Calculate all sums
   SUMX=SUMX+X(I)
   SUMY=SUMY+Y(I)
   SUMXY=SUMXY+X(I)*Y(I)
   SUMXX=SUMXX+X(I)*X(I)
   SUMYY=SUMYY+Y(I)*Y(I)
NEXT I
'
SLOPE = (N*SUMXY-SUMX*SUMY)/(N*SUMXX-SUMX*SUMX)
A=SLOPE
'
INTERCEPT=(SUMY*SUMXX-SUMX*SUMXY)/(N*SUMXX-SUMX*SUMX)
B=INTERCEPT
'
IF N=2 THEN 9950                        'Perfect fit; variance is zero.
VAR=(SUMYY-B*SUMY-A*SUMXY)/N           'Calculate variance of estimate
IF VAR<0 THEN VAR=0                     'In case of round-off errors.
'
SA=SQR(VAR*N/ABS(N*SUMXX-SUMX*SUMX)) 'Find standard error of slope
'
SB=SA*SQR(SUMXX/N)                     'Find standard error of intercept.
'
'
09950 RETURN                                'to calling program
'-------------------------------------------------------------------------
'************************** END ***************************************
'-------------------------------------------------------------------------
```

PROGRAM SEIS13J
GRM VELOCITY ANALYSIS

The generalized reciprocal method (GRM) is a technique for delineating undulating refractors, at any depth, from in-line seismic refraction data consisting of forward and reverse travel times. This program performsa velocity analysis for the determination of refractor velocity using the GRM.

EXAMPLE: Below are shown a time-distance plot of reversed bedrock refractors from a site in central Idaho. Note that the reciprocal time averages at 62.5 ms, the distance between geophones is 5 ft, and that 33 geophones have headwave arrivals from both directions. The format for the input data file is also shown. Each line in the file consists of geophone location, geophone elevation, time (in ms) from the left shot, and time (in ms) from the right shot. The numbers on each line must be separated by commas.




```
  0 ,    4654 ,     28 ,    54.5
  5 ,    4654 ,   29.5 ,      54
 10 ,    4654 ,     30 ,    52.5
 15 ,    4654 ,   30.5 ,      52
 20 ,    4654 ,     32 ,    52.5
 25 ,  4653.6 ,   35.5 ,    54.5
 30 ,  4653.2 ,   39.5 ,      55
 35 ,  4653.2 ,   40.5 ,      55
 40 ,  4653.2 ,     41 ,    54.5
 45 ,    4654 ,   40.5 ,      52
 50 ,  4654.5 ,     40 ,    49.5
 55 ,    4655 ,   41.5 ,    49.1
 60 ,  4655.5 ,     42 ,    45.5
 65 ,  4656.2 ,   43.5 ,    43.5
 70 ,    4657 ,     44 ,    43.5
 75 ,  4657.5 ,     44 ,    41.5
 80 ,  4657.2 ,   44.5 ,    41.5
 85 ,    4657 ,     45 ,      41
 90 ,  4656.5 ,   45.5 ,    40.5
 95 ,  4657.2 ,   45.5 ,    40.5
100 ,  4657.5 ,     45 ,      39
105 ,  4657.8 ,     47 ,    38.5
110 ,    4658 ,   45.5 ,    34.5
115 ,    4660 ,   46.5 ,      36
120 ,  4661.5 ,     47 ,      34
125 ,    4662 ,   48.5 ,      34
130 ,  4663.2 ,     50 ,    33.5
135 ,    4665 ,     50 ,    33.5
140 ,  4666.2 ,     51 ,      33
145 ,  4667.5 ,   52.5 ,      33
150 ,    4668 ,   52.5 ,      32
155 ,  4668.8 ,   53.5 ,    29.5
160 ,    4669 ,     55 ,    27.5
```

PROBLEM SOLUTION:

```
Reciprocal Time in msec.?  62.5
Geophone separation in feet? 5
Number of geophone locations? 33
Data File Name? Data.dat
```

XY SEP	V2 in ft/s	% ERROR	VARIANCE
0	6242.433	1.918085	.7062026
XY SEP	V2 in ft/s	% ERROR	VARIANCE
1	6358.678	2.067671	.7211304
XY SEP	V2 in ft/s	% ERROR	VARIANCE
2	6452.621	2.355504	.8262034
XY SEP	V2 in ft/s	% ERROR	VARIANCE
3	6527.548	2.815749	1.045508
XY SEP	V2 in ft/s	% ERROR	VARIANCE
4	6622.517	3.191875	1.178913

The XY separation and velocity that results in the lowest % error and Variance are considered optimum.

PROGRAM LISTING:

```
1012 '                          Moscow, Idaho
1014 '                         (208) 885-7977
1016 'Refraction Interpretation
1018 ' using the GRM.
2000 '-------------------------------------------------------------------
2010 '
2012 '                       Initialize Variables
2014 '
2015 DIM X(100),Y(100)                'Work Space for Best Fit Line Routine
2016 DIM DIST(100), ELEV(100)       'Distances and elev of the phones
2017 DIM TA(100), TB(100)             'Arrival times from left and right
2018 '                                 shots respectively in msec.
2500 '-------------------------------------------------------------------
2502 '
2504 '                          Main Program
2506 '
2510 GOSUB 3000                       'Data Entry
2512 '
2514 GOSUB 4000                       'Analyze Minus-Terms
2516 '
2520 END
3000 '-------------------------------------------------------------------
3010 '
3012 '                          Data Entry
3014 '
3020 INPUT "Reciprocal Time in msec.";TAB
3022 '
3024 INPUT "Geophone Separation in ft"; GEOSEP
3026 '
3028 INPUT "Number of geophone locations";NPHONES
3030 '
3032 INPUT "Data File Name";FILE$
3035 OPEN FILE$ FOR INPUT AS #2
3036 '
3037 'Data file should consist of four numbers on each line separated by
3038 ' commas. All distances must be represented at regular interval past
3039 ' the first given value. If no time is available at any given distance,
3040 ' a zero should be entered.
3041 FOR I=1 TO NPHONES: INPUT #2, DIST(I),ELEV(I),TA(I),TB(I):NEXT
3045 CLOSE#2
3046 '
3070 RETURN
4000 '-------------------------------------------------------------------
```

```
4005 '
4007 '                              Minus Term
4009 '
4010 FOR XY=0 TO 4                    'Try 5 possible values of XY
4012   IF XY=0 THEN OPEN "GRM0.DAT" FOR OUTPUT AS #1
4013   IF XY=1 THEN OPEN "GRM1.DAT" FOR OUTPUT AS #1
4014   IF XY=2 THEN OPEN "GRM2.dAT" FOR OUTPUT AS #1
4015   IF XY=3 THEN OPEN "GRM3.dat" FOR OUTPUT AS #1
4016   IF XY=4 THEN OPEN "GRM4.dat" FOR OUTPUT AS #1
4017   KOUNT=0
4020   FOR I=1 TO (NPHONES-XY)
4022     IF TA(I+XY)=0 OR TB(I)=0 THEN 4060
4023     KOUNT=KOUNT+1
4025 '
4030     CENTER=XY/2+I-1             'Calculate location of midpoint between
4031                                 'receiving geophones.
4033 '
4035     TM=( TA(I+XY)-TB(I) +TAB)/2  'TM is the minus-term
4037 '
4040     DCENTER = GEOSEP*CENTER + DIST(1) 'Find distance to plotting point
4045     PRINT#1,DCENTER,TM+5*XY    'Save results for later plotting.
4050 '                               Scale times for plotting
4052     X(I)=DCENTER               'Set up arrays for Best Fit Routine.
4054     Y(I)=TM
4060   NEXT I
4063   CLOSE
4065   N=KOUNT
4070   GOSUB 9000                  'Find Best fit straight line
4075 '
4080   V2=1/SLOPE*1000            'Calculate best fit velocity of lower layer.
4090   ERRR=SA/SLOPE*100          'Find % error of fit in terms of slope
4100   PRINT "XY SEP","V2 in ft/s","% ERROR","VARIANCE"
4110   PRINT XY,V2,ERRR,VAR
4200 NEXT XY
4300 RETURN
8999 '-------------------------------------------------------------------------
9000 'LSTSQ1    vers. 1             KF Sprenke                    Nov 20, 1985
9010 '                           University of Idaho
9020 '                              Moscow, Idaho
9030 '                             (208) 885-7977
9040 '
9050 '
9060 'LSTSQ1 is a subroutine for the fitting of a best fit straight line in
9070 'a least square sense to N data points X(1),Y(1)  X(2),Y(2)  X(3),Y(3)
9080 '.........X(N),Y(N).
9090 'The best fit slope is A, the best fit y-intercept is B.
9100 '
9110 '
9120 '                      **FORMULAS**
9130 '
9140 'The normal equations solved for slope A and y-intercept B are:
9150 '
9160 '              N sum (xy) - sum (x) sum (y)
9170 '       A =    ----------------------------
9180 '              sum (x) sum (x) - N sum (xx)
9190 '
9200 '
9210 '             sum (xx) sum (y) - sum (x) sum (y)
9220 '       B =   ----------------------------------
9230 '                sum (x) sum (x)  - N sum (xx)
9240 '
9250 '
9260 'Further useful statistics include VAR, the variance of the estimate,
9270 'from which the standard error of the slope SA and the standard error of
9280 'the y-intercept SB may be calculated.
9290 '
9300 '              sum (yy) - B sum (y) - A sum (xy)
9310 '       VAR =  ---------------------------------
9320 '                            N
```

```
9330 '
9340 '
9350 '                          VAR  N
9360 '       SA =  SQR (---------------------------  )
9370 '                  N sum (xx) - sum (x) sum (x)
9380 '
9390 '
9400 '                         sum (xx)
9410 '       SB =  SA  SQR (-----------)
9420 '                           N
9430 '
9440 '
9450 '
9460 '
9470 'GLOBAL ARGUMENTS FROM CALLING PROGRAM
9480 '
9490 '
9500 ' N                                  'Number of data points
9510 ' X(N)                               'Array of N x coordinates
9520 ' Y(N)                               'Array of N y coordinates
9530 '
9540 ' DIM X(N),Y(N)                      'DIM statement must appear in calling
9550 '                                    'program with explicit value for N.
9560 '
9570 '
9580 ' INITIALIZE VARIABLES
9590 '
9600 SUMX=0:SUMY=0                       'Sum of x; sum of y coordinates.
9610 SUMXX=0:SUMYY=0:SUMXY=0             'Sum of cross products
9620 VAR=0                               'Variance of estimate
9630 SA=0                                'Standard error of slope
9640 SLOPE=0                             'Best fit slope
9650 A=SLOPE                             'Abbreviation for slope in equations
9660 INTERCEPT=0                         'Best fit Y-intercept
9670 B=INTERCEPT                         'Abbreviation for intercept
9680 SB=0                                'Standard error of intercept
9690 I=0                                 'Counter in FOR/NEXT LOOP
9700 '
9710 '
9720 '
9730 '
9740 FOR I=1 TO N                        'Calculate all sums
9750    SUMX=SUMX+X(I)
9760    SUMY=SUMY+Y(I)
9770    SUMXY=SUMXY+X(I)*Y(I)
9780    SUMXX=SUMXX+X(I)*X(I)
9790    SUMYY=SUMYY+Y(I)*Y(I)
9800 NEXT I
9810 '
9820 SLOPE = (N*SUMXY-SUMX*SUMY)/(N*SUMXX-SUMX*SUMX)
9830 A=SLOPE
9840 '
9850 INTERCEPT=(SUMY*SUMXX-SUMX*SUMXY)/(N*SUMXX-SUMX*SUMX)
9860 B=INTERCEPT
9870 '
9875 IF N=2 THEN 9950                     'Perfect fit; variance is zero.
9880 VAR=(SUMYY-B*SUMY-A*SUMXY)/N         'Calculate variance of estimate
9885 IF VAR<0 THEN VAR=0                  'In case of round-off errors.
9890 '
9900 SA=SQR(VAR*N/ABS(N*SUMXX-SUMX*SUMX)) 'Find standard error of slope
9910 '
9920 SB=SA*SQR(SUMXX/N)                   'Find standard error of intercept.
9930 '
9940 '
9950 RETURN                               'to calling program
9960 '-------------------------------------------------------------------------
9970 '************************** END ***************************************
9980 '-------------------------------------------------------------------------
```

PROGRAM SEIS13K
GRM TIME-DEPTH INTERPRETATION

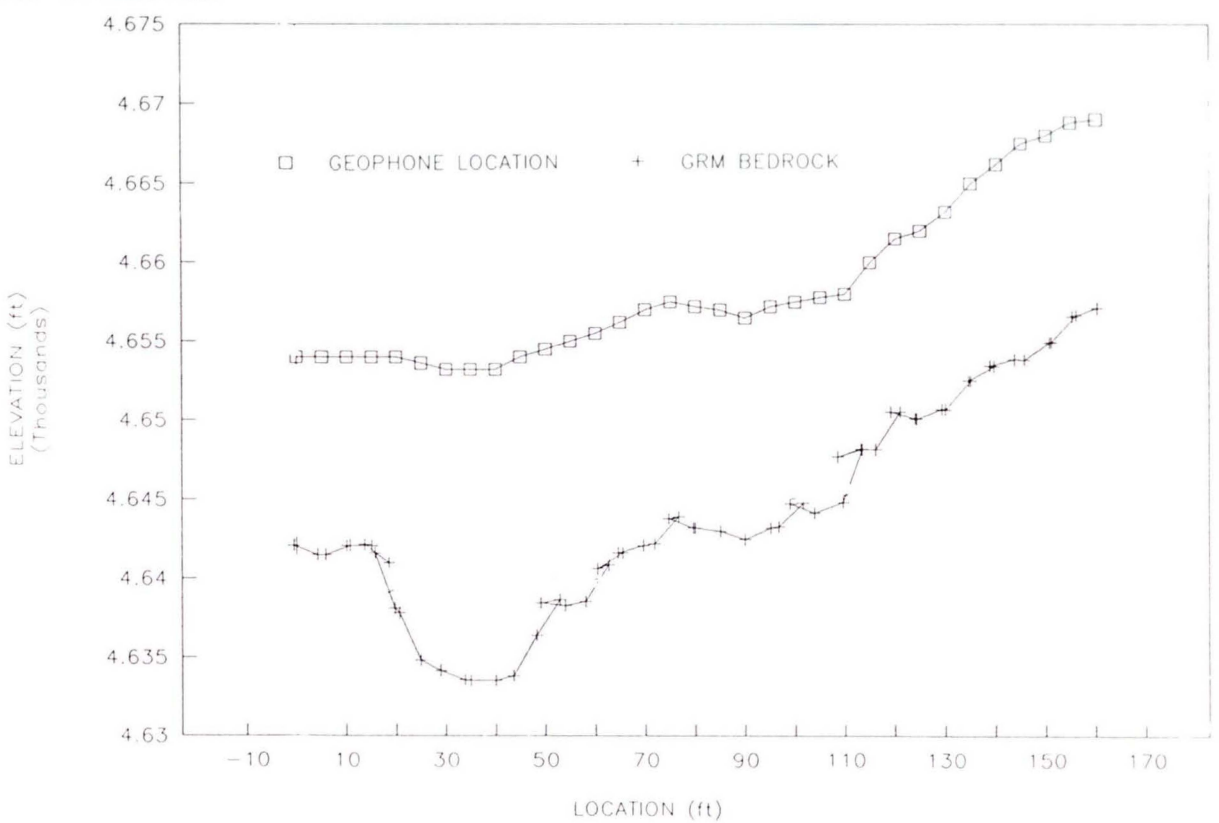
This program computes the elevations of the refracting surface using the generalized reciprocal method (GRM). Prior to using this program one needs to know the optimum XY distance and optimum refractor velocity from Program SEIS13J. The velocity of the overlying layer must also be known prior to using this program. The input file for this program is identical to that of Program SEIS13 J. The output file GRMB.DAT contains the locations and elevations of migrated points on the refractors surface. For convenience, another output file, GRMA.DAT, contains the locations and elevations of the geophones. These files can then be imported into any standard graphics program for plotting a cross-section of the results.

EXAMPLE: Given a top layer velocity of 1170 ft/s, determine the elevations of the bedrock surface for the data presented in the example for Program SEIS13J.

PROBLEM SOLUTION:

```
Reciprocal Time in msec? 62.5
XY Distance in ft? 0
Top Layer Velocity in ft/s?  1170
Lower Layer Velocity in ft/s? 6242
Geophone Separation in ft? 5
Number of geophone locations?  33
Data File Name?  DATA.DAT
```

File GRMB.DAT and GRMA.DAT after plotting should look as follows, the first column being the horizontal location of the refracting point, the second being its elevation:



File GRMB.DAT is as follows:

-.7093726	4642.11
4.255159	4641.516
5.744841	4641.516
10.70937	4642.11
10	4642.089
15	4642.089
13.58125	4642.174
18.43938	4640.991
15.7083	4641.621
19.63537	4638.126
20.61075	4637.822
24.89251	4634.84
28.865	4634.177
33.82953	4633.582
35	4633.547
40	4633.547
43.5114	4633.864
48.19218	4636.421
48.19218	4636.421
52.87296	4638.679
48.94659	4638.455
53.90367	4638.301
58.08967	4638.553
62.74882	4640.867
60.44336	4640.618
65.4345	4641.615
64.56551	4641.615
69.55665	4642.118
71.77343	4642.217
76.63156	4643.9
74.59211	4643.808
79.58325	4643.211
80	4643.205
85	4643.005
85	4643.005
90	4642.505
90	4642.505
95	4643.205
96.66703	4643.304
101.5252	4644.787
98.85613	4644.747
103.7763	4644.157
109.4868	4644.858
113.4139	4648.153
108.4483	4647.694
113.2266	4648.222
116.0641	4648.137
120.9843	4650.527
119.0158	4650.527
123.9359	4650.137
124.2906	4650.11
129.2552	4650.716
130	4650.694
135	4652.493
134.6276	4652.499
139.6187	4653.402
138.8561	4653.447
143.7763	4653.857
145.8158	4653.826
150.7803	4654.921
151.1705	4654.95
156.0907	4656.64
155.3636	4656.596
160.3547	4657.094

PROGRAM LISTING:

```
'                          Moscow, Idaho
'                         (208) 885-7977
'Refraction Interpretation
' using the GRM with velocities and XY distance given.
'-----------------------------------------------------------------------
'
'                       Initialize Variables
'
'
DIM DIST(100), ELEV(100)      'Distances and elev of the phones
DIM TA(100), TB(100)             'Arrival times from left and right
'                                 shots respectively in msec.
DEF FNASIN(X)=ATN(X/SQR(1-X*X))
'-----------------------------------------------------------------------
'
'                         Main Program
'
GOSUB 3000                        'Data Entry
'
GOSUB 4000                        'Analyze Plus-Terms
'
END
03000 '---------------------------------------------------------------------
'
'                         Data Entry
'
INPUT "Reciprocal Time in msec.";TAB
INPUT "XY Distance in ft";XY
INPUT "Top Layer Velocity in ft/s";V1
INPUT "Lower layer velocity in ft/s"; V2
INPUT "Geophone Separation in ft"; GEOSEP
'
INPUT "Number of geophone locations";NPHONES
'
INPUT "Data File Name";FILE$
OPEN FILE$ FOR INPUT AS #2
'
'Data file should consist of four numbers on each line separated by
' commas. All distances must be represented at regular interval past
' the first given value. If no time is available at any given distance,
' a zero should be entered.
FOR I=1 TO NPHONES: INPUT #2, DIST(I),ELEV(I),TA(I),TB(I):NEXT
CLOSE#2
'
OPEN "GRMA.DAT" FOR OUTPUT AS #3      'Create plot file for elevations
FOR I=1 TO NPHONES: PRINT#3,DIST(I),ELEV(I):NEXT
CLOSE#3
RETURN
04000 '---------------------------------------------------------------------
'
'                          Plus Term
'
OPEN "GRMB.DAT" FOR OUTPUT AS #1   'Open file to hold bedrock points
'                                   for X-Y plotter.
  KOUNT=0
  FOR I=1 TO (NPHONES-XY)
    IF TA(I+XY)=0 OR TB(I)=0 THEN 4060
    KOUNT=KOUNT+1
'
    CENTER=XY/2+I-1            'Calculate location of midpoint between
                               'receiving geophones.
'
    TP=( TA(I+XY)+TB(I) -TAB-XY*GEOSEP*1000/V2)/2  'TP is the plus-term
    D=V1*V2*TP/(1000*SQR(V2*V2-V1*V1)) 'Find perpendicular distance
'
    DCENTER = GEOSEP*CENTER + DIST(1) 'Find distance to plotting point
```

```
    ECENTER=(ELEV(I+XY)+ELEV(I))/2   'Find mean elevation of geophone pair
    IF KOUNT=1 THEN 4055
    ALPHA=FNASIN((D-DOLD)/(2*GEOSEP)) 'Find dip of refractor between this
                                      'pair and previous pair of phones.
      PRINT#1,(DCOLD-DOLD*SIN(ALPHA)),(ECOLD-DOLD*COS(ALPHA))
      PRINT#1,(DCENTER-D*SIN(ALPHA)),(ECENTER-D*COS(ALPHA))
'
'
04055     DOLD=D                      'Store values for use in next calculation
    DCOLD=DCENTER
    ECOLD=ECENTER
04060   NEXT I
  CLOSE
  N=KOUNT
RETURN
'-------------------------------------------------------------------------
END   '                 END OF PROGRAM
```

Geophysical Exploration for Voids Along a Proposed Road Location
Kessler Creek Project

Nezperce National Forest

by

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and

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Intermountain Research Station

March 10, 1986

Introduction

A proposed forest road location near Kessler Creek in the ezperce National Forest crosses an area of sinkholes. If ubsurface voids are also present in this area, a severe hazard o logging operations exists. In this study, three geophysical ngineering methods--seismic refraction, resistivity, and ground-robing radar--were deployed to locate possible voids.

Study Area

The location of the study area is west of Riggins, Idaho ear Kessler Creek in the Nezperce National Forest. Figure 1 is a opographic map of the general area of the study site. Figure 2 s a basemap of the immediate study site showing the approximate ocations of known sinkholes, the proposed road location crossing he study area in a NW-SE direction, and a grid of lines cut for he geophysical surveys.

Seismic Method

A Geometrics 12-channel seismograph was used to determine he depth to bedrock and the seismic velocities of near surface aterials at approximately 15 foot intervals along each line. The nergy source was a sledge hammer; the receivers were 40 Hz eophones. To ensure reversed coverage, shotpoints were placed ff both ends of the geophone spreads.

The seismic records obtained are reproduced in Appendix A. Travel times of first arrivals were picked, tabulated, and interpreted using the reciprocal method. The BASIC computer program used to process the results is listed in Appendix B. The program output showing shot receiver distances, arrival times, depths to bedrock, and velocity anomalies is given in Appendix C. Cross-sections of each line showing the seismic results are in Appendix D.

Figure 3 shows a contour map of bedrock depths based on the seismic results. The depth to bedrock at the study site varies from 8 to 16 feet. The seismic velocity of the soil layer varies from 1250 to 1600 ft/s with a mean value of 1390 ft/s. The velocity of bedrock is in the range 6000 to 9000 ft/s. The bedrock depressions apparent on Figure 3 may indicate old sinks which have subsequently filled with debris.

Unusual reversed polarities occur on some of the first breaks on seismic record DS (Figure 4). The reversed polarities correspond to the northern geophone locations on cross line 4. This record was re-shot and the reversed polarities reoccurred. However, the reversed polarities do not appear on the seismic record for the same line shot from the north. Reversed polarities theoretically might indicate the presence of a free surface (void) in the sub-surface, but such an interpretation is highly speculative.

Resistivity Method

Resistivity profiling was performed over the survey grid using a ABEM Terrameter. A basic Wenner Array with an electrode spacing of 20 ft was employed. Distances between successive measurements on each line was also 20 ft. The electrical ground resistances measured are contoured in Figure 5. Profiles of ground resistance are plotted along with the seismic profiles in Appendix D.

In general, subsurface voids would be expected to show relatively high ground resistance. However, if the cavities are filled with clay or water, they could be electrically conductive. Figure 5 shows a general decrease in ground resistance from northeast to southwest. Very erratic countours occur in the sink filled area in the southwest portion of the study site. This pattern does not occur in the remainder of the study site indicating more stable subsurface conditions away from the sinks. The ground resistance contours show little evidence for a continuous large cave system in the study site.

Ground-Probing Radar Method

Ground-probing radar measurements were carried out in the study site using a OYO YL-R2 Georadar System. In this method, electromagnetic impulses are continuously directed into the ground by a transmitting antenna; a receiving antenna then receives returning waves from the subsurface. The most important factors in the radar response at a site are the conductivity and

dielectric constant of the subsurface material; these factors are in turn strongly related to the rock types and water contents of the material. Ground conductivity largely determines the skin depth, that is, the depth of penetration of the radar waves. In clays, penetration may be only a few millimeters, but in coarser, more resistive soils, penetration of several tens of feet is possible. Radar waves are reflected at the boundaries between media of different dielectric constant or different conductivities. Hence, geological boundaries such as the bedrock surface and hydrologic boundaries such as the water table often produce radar reflections. The velocity of radar waves is controlled by the dielectric constant of the medium. In general, the more moisture present, the greater the dielectric constant and the slower the radar velocity. In a vacuum, radar waves propagate at the speed of light (about 1 ft per nannosecond); in water, the waves travel at about 10% of the speed of light (0.1 ft/ns). The radar velocities of soils and rocks will fall between these two extremes.

Figure 6 shows a radar velocity profile obtained at the study site. For this type of survey, one of the antennas is kept in a fixed position while the other is moved away. The degree to which the various received events move out on the resultant profile allows the events to be identified. The air wave--the radar wave travelling through the air from the source antenna to the receiving antenna--will move out on the velocity profile at a rate of about 1 ns per foot. The direct wave which travels through the upper soil layer will move out at a faster rate

ecause it travels slower than the speed of light. At the study ite, the direct wave velocity was found to be 0.246 ft/ns about 25% of the speed of light). Such a soil velocity orresponds to a dielectric constant of about 16 and a near urface volumetric moisture content of 28%. Reflected events on adar velocity profiles move out on the record in the form of yperbolic curves. The rate of curvature of reflected events epends on the depth of the reflector and the average velocity of he material above the reflecting layer. A BASIC program Appendix B) was written to calculate the average velocity to and he depth of the reflection events apparent on the velocity rofile. The deepest discernable reflector on this velocity rofile yields an average velocity of 0.339 ft/ns which orresponds to a dielectric constant of 8.65 and a volumetric oisture content of 18%. Hence the volumetric moisture content (saturation x porosity) tends to decrease with depth at the study ite. The depth to the deepest reflector on the velocity profile as found to be 12.9 ft--a value in close agreement with the epth to bedrock determined by seismic refraction at the same location (along the base line between cross lines 2 and 3).

Continuous wiggle trace radar profiles were run on all the lines on the grid at the study site. No antenna separation was used. The records obtained are in Appendix E. Figure 7 shows a radar profile along Line 3 made in the "scan mode" in which positive polarities are shown in black, negative in white. Figure 7 shows discontinuous reflectors from the upper 10 feet of the soil and intermittent reflectors possibly from within bedrock at

epths of about 20 feet. These reflectors could be due to the resence of cavities. However, the resistivity data does not upport this interpretation. The reflectors could also be due to edrock fractures.

No clear reflection from the bedrock surface is apparent. igure 6, the velocity profile, indicates that a stronger bedrock eflection may have been observed had an antenna-receiver eparation of about 5 feet been employed in the field. The two orizontal events apparent on Figure 6 are instrument noise.

The wiggle trace profiles show variations in the arrival imes of reflections from within the soil layers. The locations f anomalous zones showing deeper soil reflectors are plotted long with the seismic depths to bedrock on Figure 3. A orrelation seems to exist between the location of deeper eflectors in the soil layers and the location of bedrock epressions as seen on the seismic results; this observation einforces the interpretation that the bedrock depressions are ld debris filled sinks.

Summary and Recommendations

Three geophysical methods--seismic refraction, resistivity, nd ground-probing radar--were used in an attempt to locate ossible voids along a proposed forest road location near Kessler reek in the Nezperce National Forest. The seismic results ndicated the presence of a number of bedrock depressions which ay be old debris filled sinks. The resistivity results gave no lear indication of the presence of a cavern system although very

ratic ground resistances were noted in the neighborhood of own sinkholes. The ground-probing radar system achieved a enetration of about 10-20 feet. The wiggle trace records did not general record returning radar energy from depths below about feet. Thus, over most of the site, direct detection of ssible voids was not achieved. This may have been due to a lack reflectors (such as voids) within the bedrock. More likely, is was a result of poor field technique and incorrect nstrument settings. The radar did detect deeper reflections in he soil at locations corresponding to the seismically determined edrock depressions.

The occurrence of sinks with surface expression and of old ebris filled sinks with seismic expression in the study site ndicates that the area does suffer a hazard from the possible resence of voids in the carbonate bedrock. Road construction hould be preceeded by exploratory drilling for possible voids. edrock will be encountered at a depth of from 10 to 16 feet long the proposed road location in the study site.

FIGURE CAPTIONS

Figure 1. Topographic map of the Kessler Creek area showing the location of the study site in the Nezperce Forest east of Riggins, Idaho.

Figure 2. Base map of the Kessler Creek study site showing the location of known sinkholes and the survey grid cut for geophyysical measurements. The proposed forest road location is also shown.

Figure 3. Depths to bedrock at the Kessler Creek site as determined by seismic refraction. Locations of interpreted ground-probing radar anomalies are also shown.

Figure 4. A seismic refraction record shot to the north along cross line 4. Reversed polarities are apparent on traces 7 to 11.

Figure 5. Ground resistance contours at the Kessler Creek site as determined by the resistivity method. The resistance readings were taken with a Wenner array at an electrode spacing of 20 ft.

Figure 6. A ground-probing radar velocity profile obtained at the Kessler Creek site.

Figure 7. A ground-probing radar continuous profile record from line 3. Reflections from within soil layers occur to a depth of about 13 feet. Apparent reflections from within bedrock occur at a depth of about 20 feet primarily at the baseline end of the profile. The bedrock surface as determined by seismic refraction is plotted for comparison.

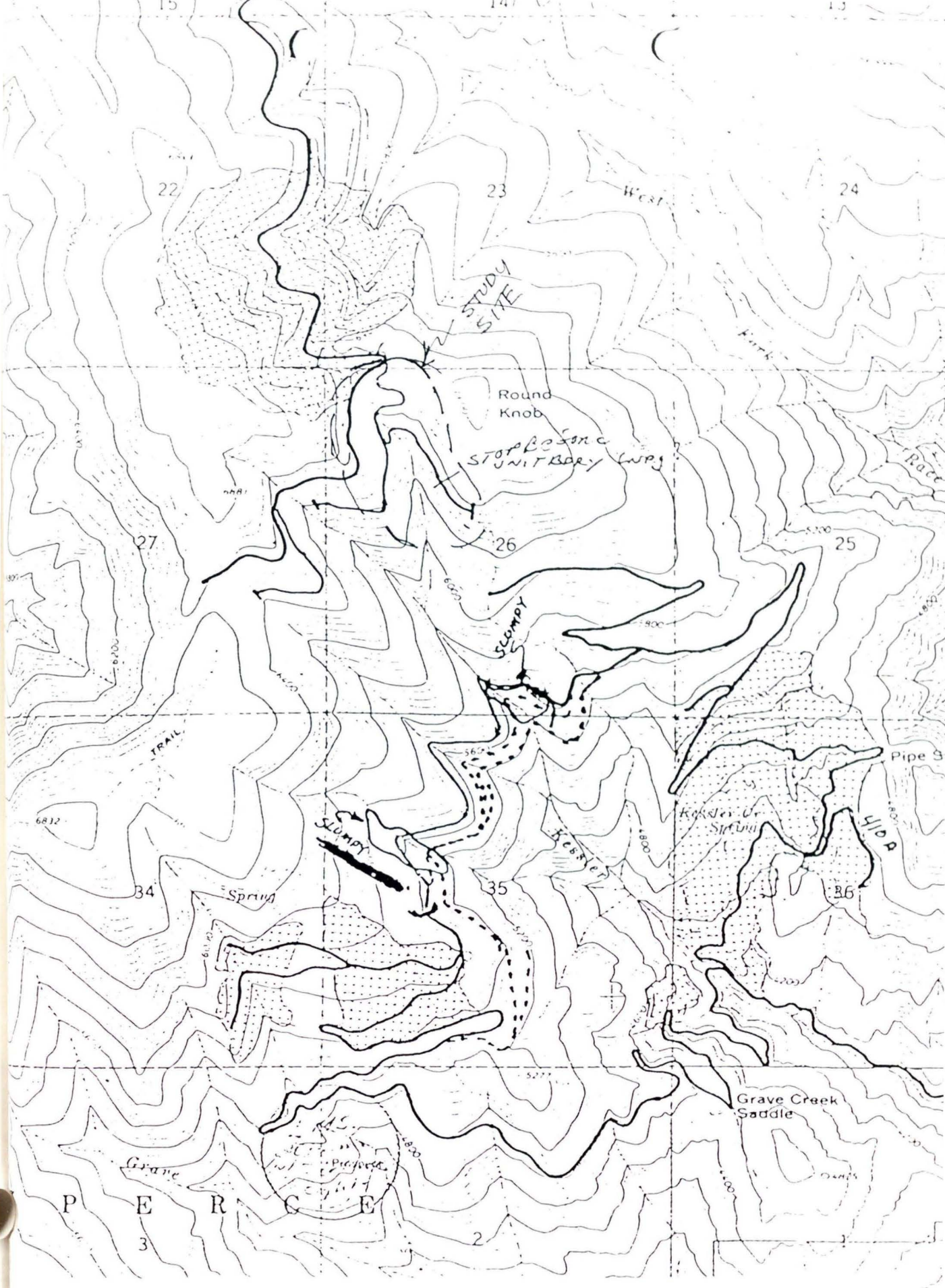
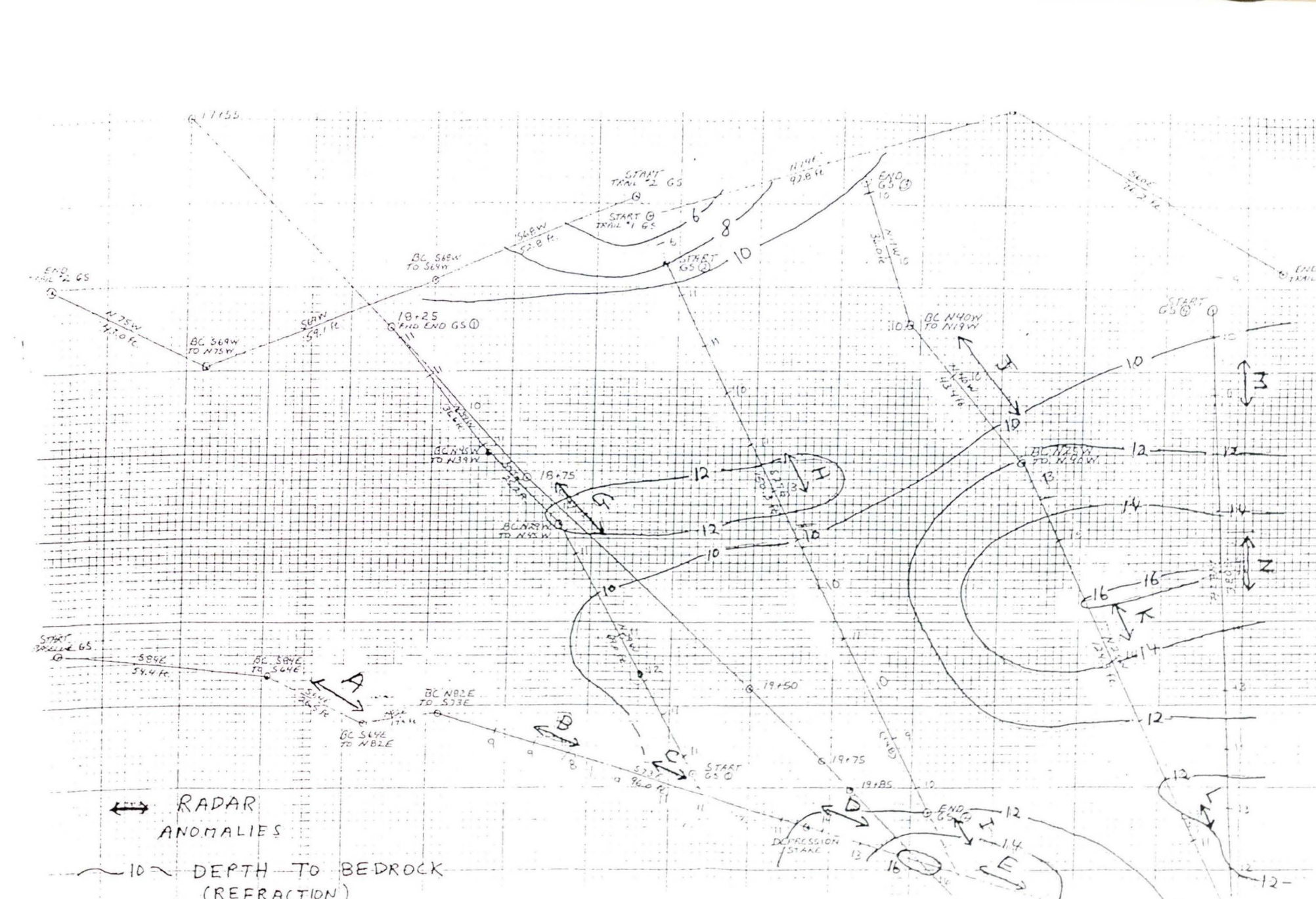


Figure 1. Topographic map of the Kessler Creek area showing the location of the study site in the Clearwater Forest east of Riggins, Idaho.


RADAR ANOMALIES
10 DEPTH TO BEDROCK (REFRACTION)
START TRAIL 2 GS
START TRAIL 1 GS
END TRAIL 2 GS
START GS ①
END GS ①
START GS ②
END GS ②
START GS ③
END GS ③
BC S68W TO S69W
BC N40W TO N19W
BC N45W TO N39W
BC N78W TO N50W
BC N82W TO N90W
BC S84E TO S64E
BC S64E TO N82E
BC N82E TO S73E
DEPRESSION STAKE
18+25 END END GS ①
18+75
19+50
19+75
19+85
A
B
C
D
E
F
G
H
J
K
L
Z

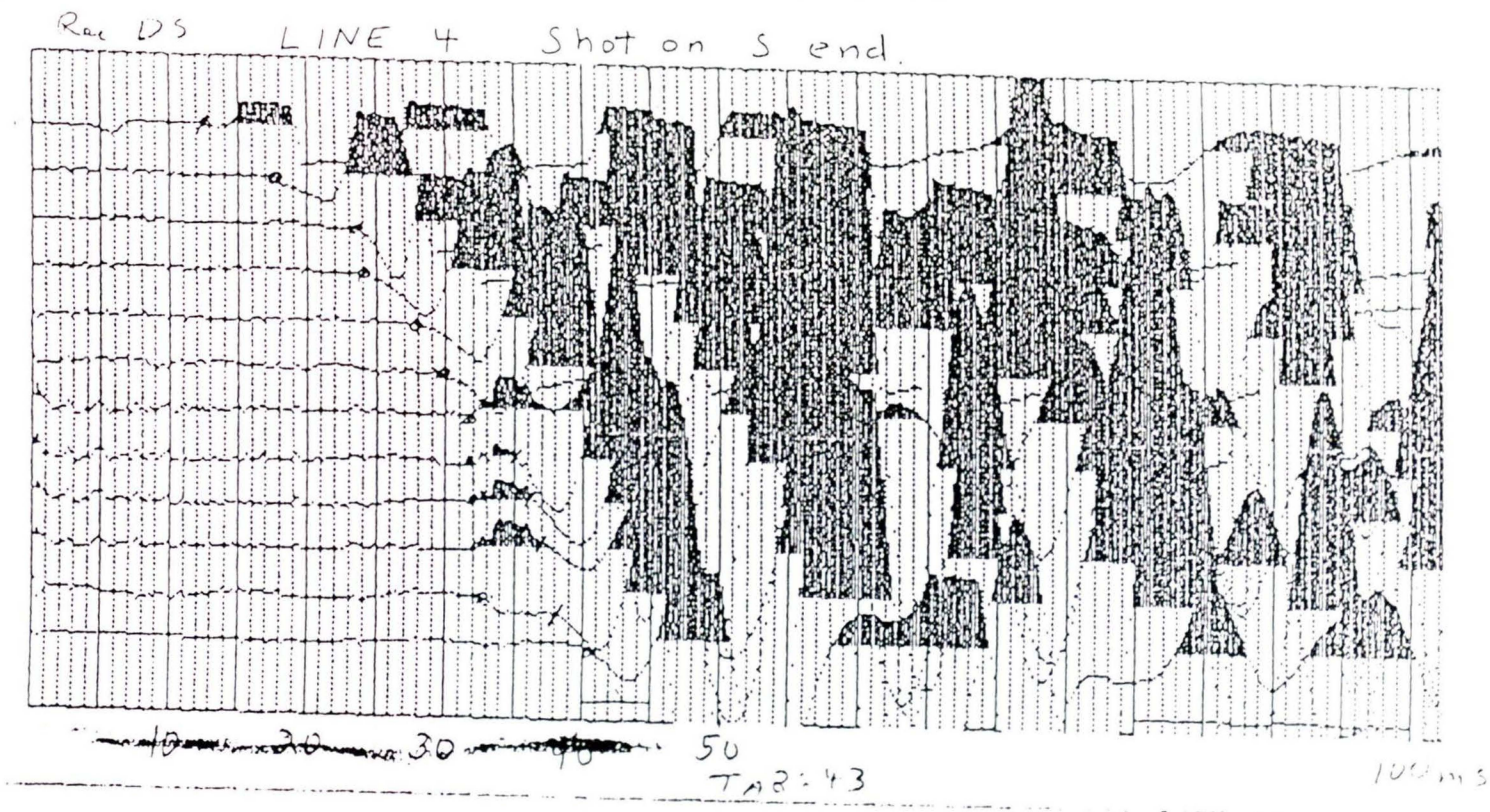


Figure 4. A seismic refraction record shot to the north along cross line 4. Reversed polarities are apparent on traces 7 to 11.

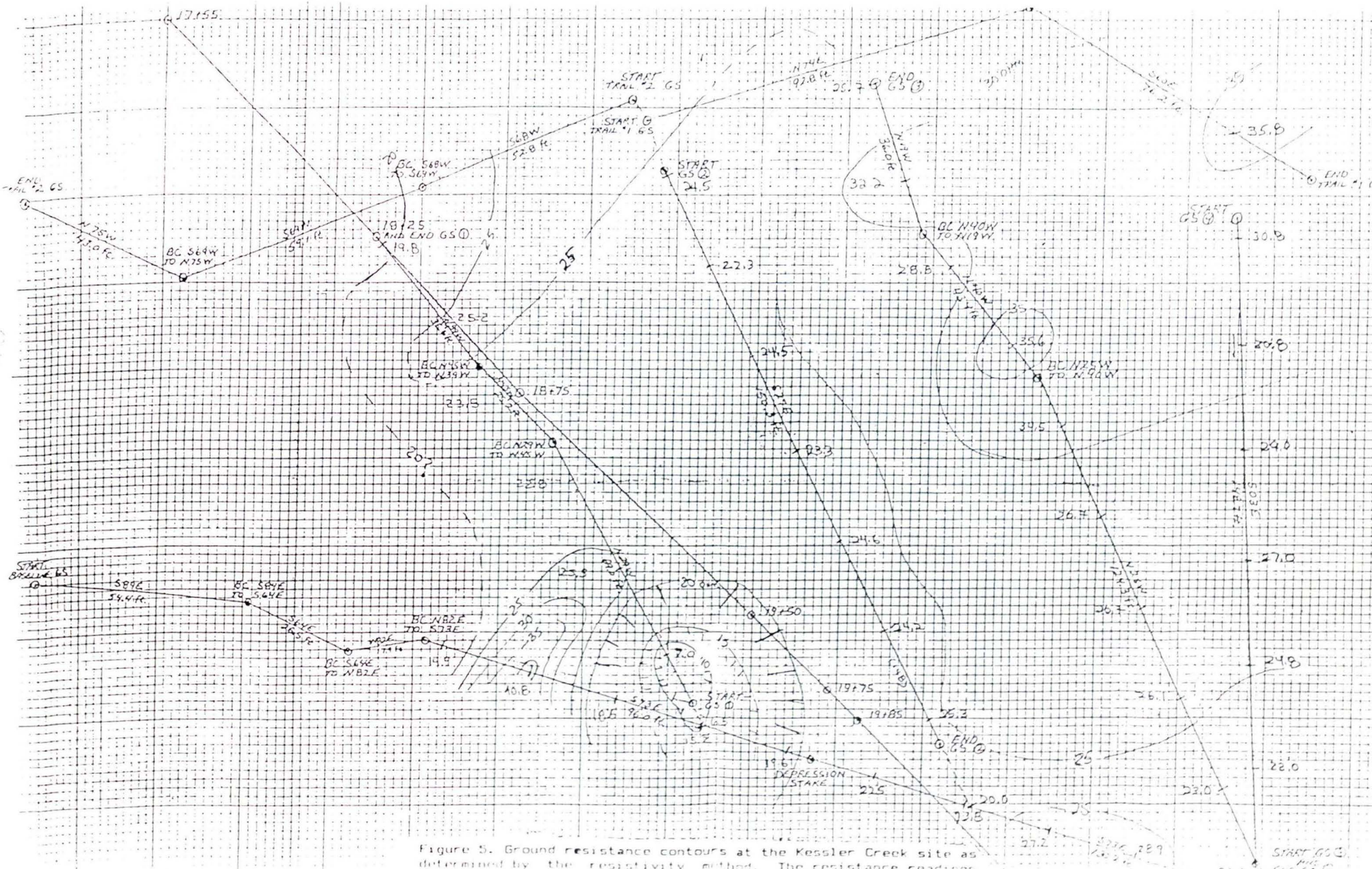


Figure 5. Ground resistance contours at the Kessler Creek site as determined by the resistivity method. The resistance readings were taken with a Wenner array at an electrode spacing of

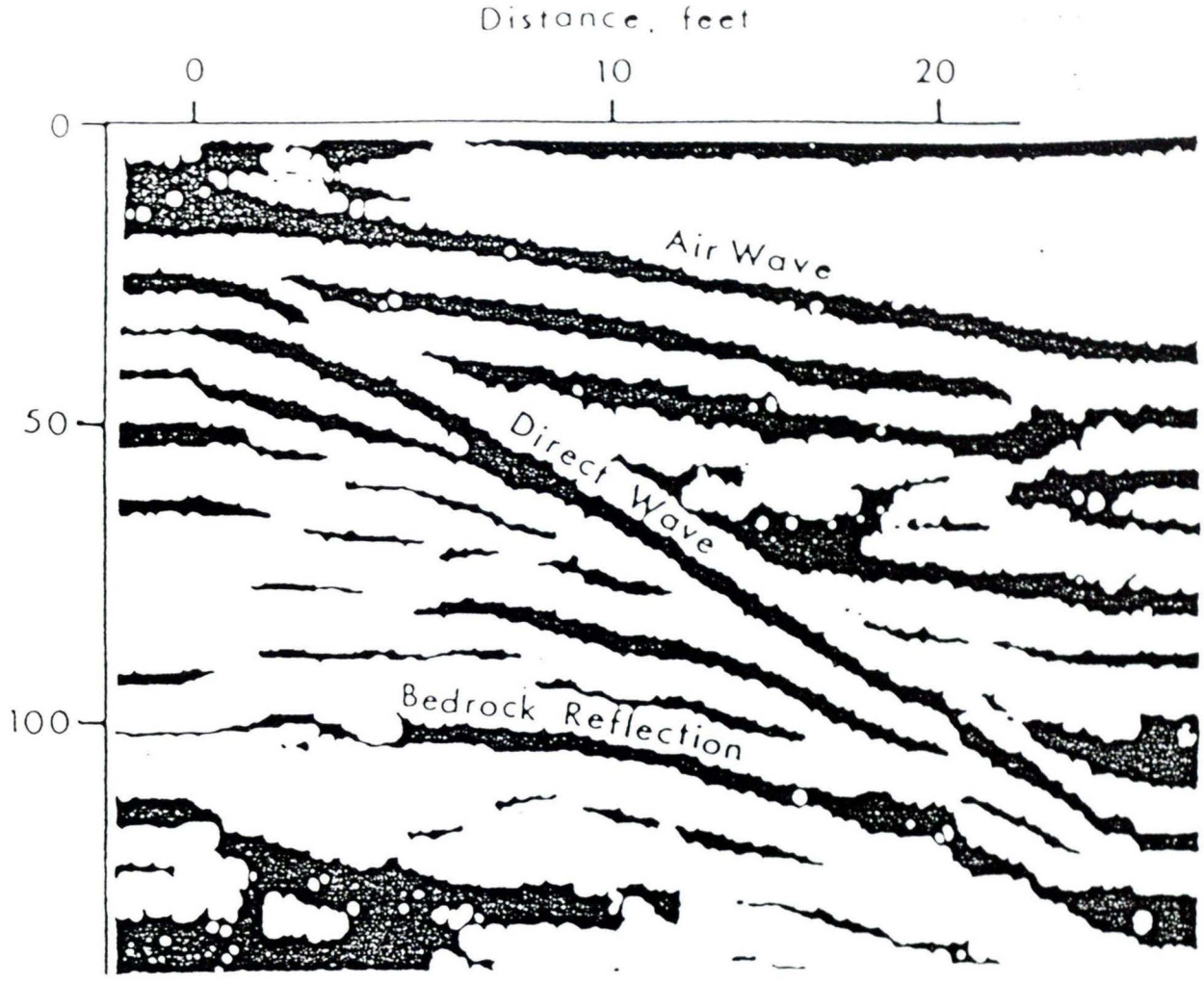


Figure 6. Radar velocity profile obtained at the study site.

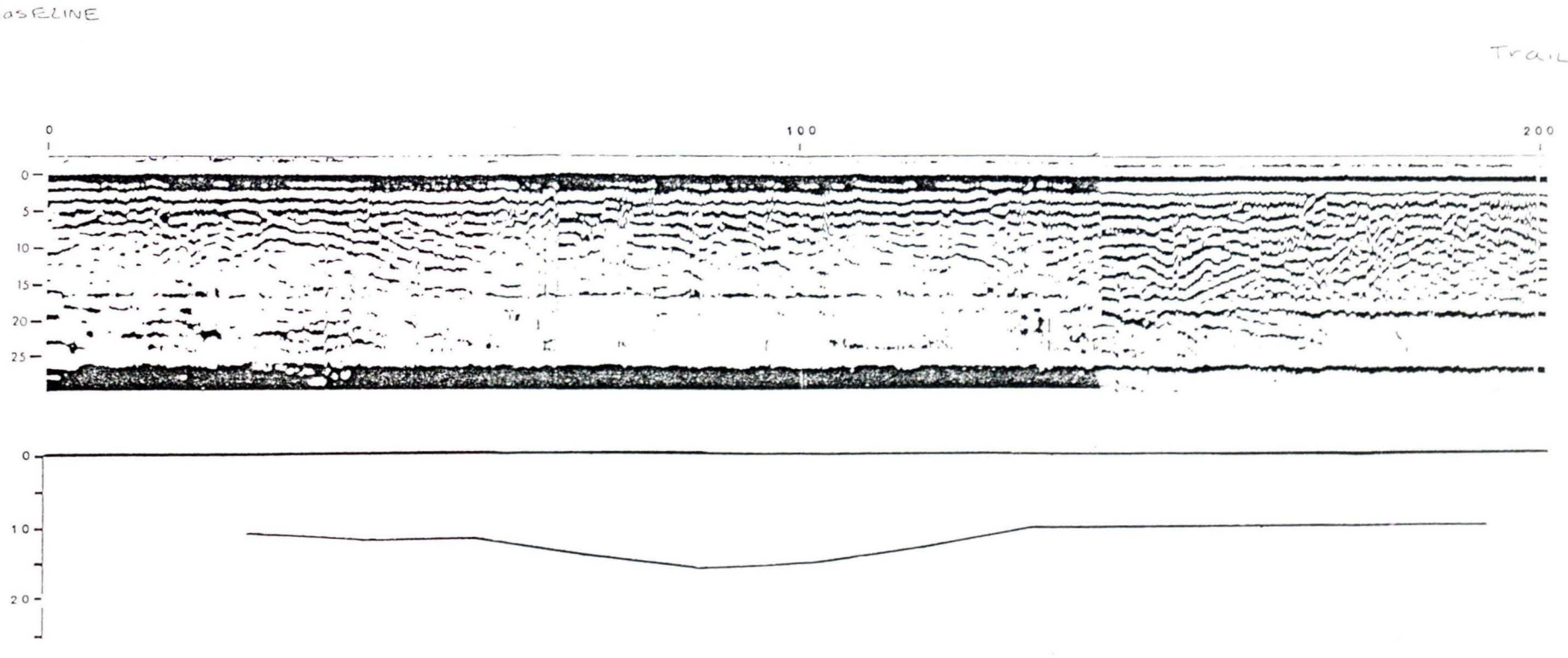
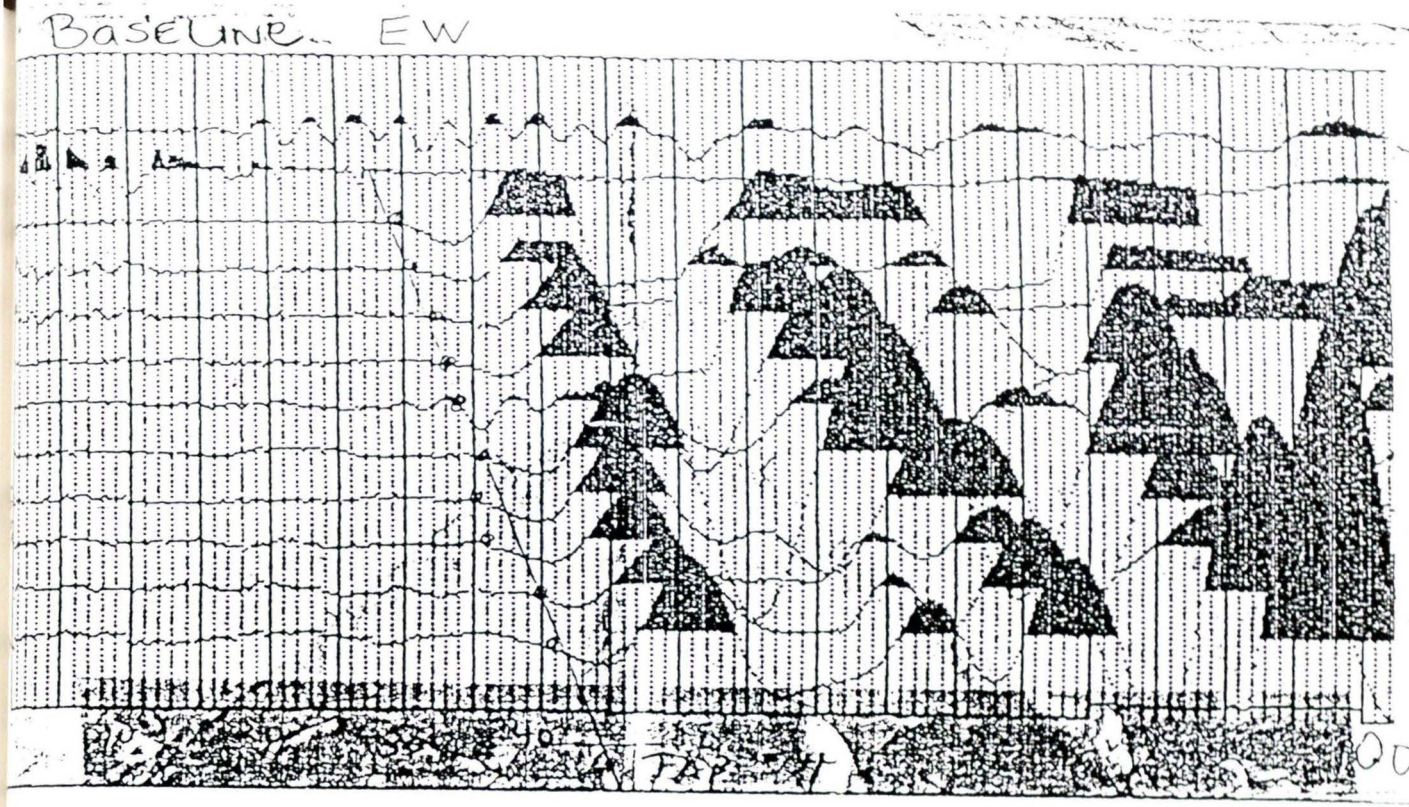
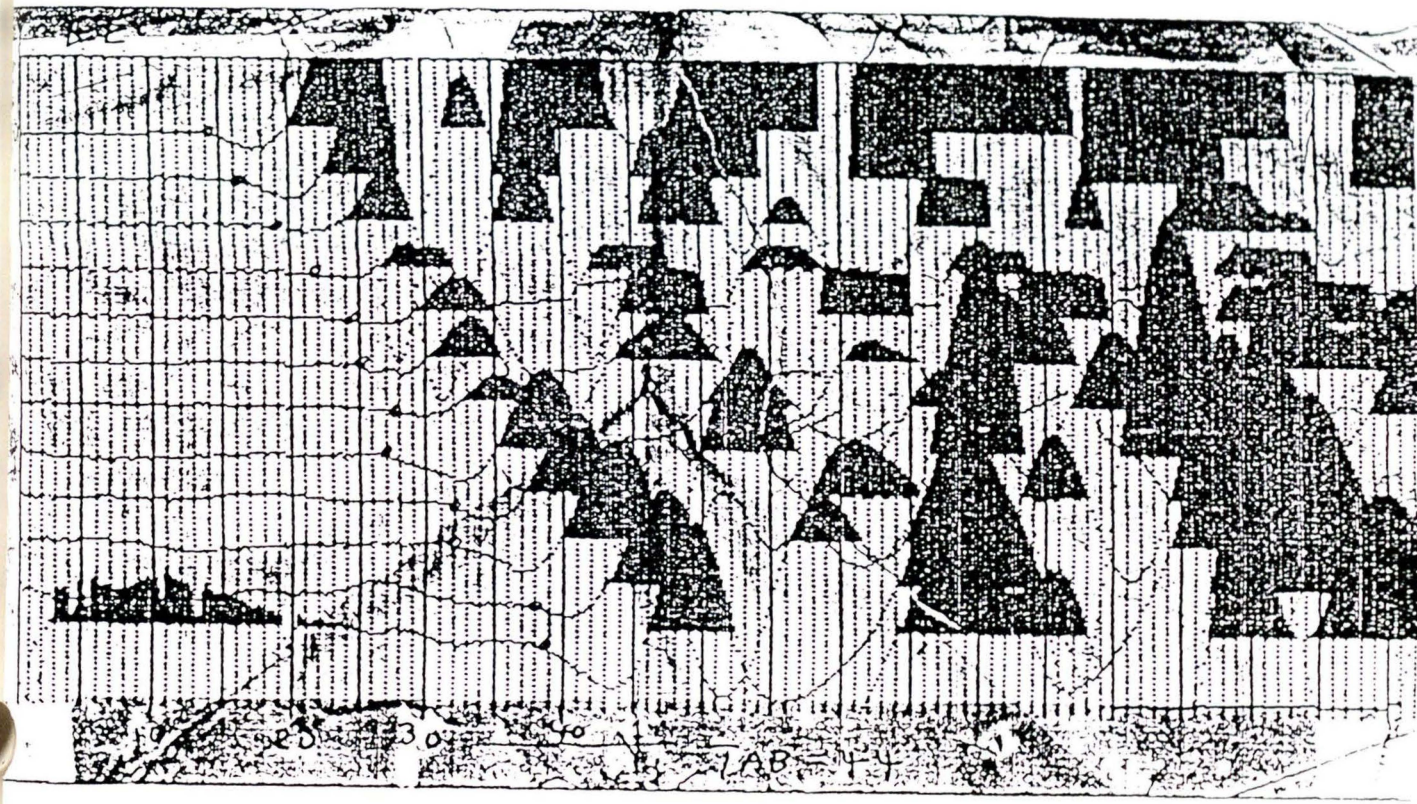


Figure 7. A ground-probing radar continuous profile record from Line 3. Reflections from within soil layers occur to a depth of about 13 feet. Apparent reflections from within bedrock occur at a depth of about 20 feet primarily at the baseline end of the profile. The bedrock surface as determined by seismic refraction is plotted for comparison.

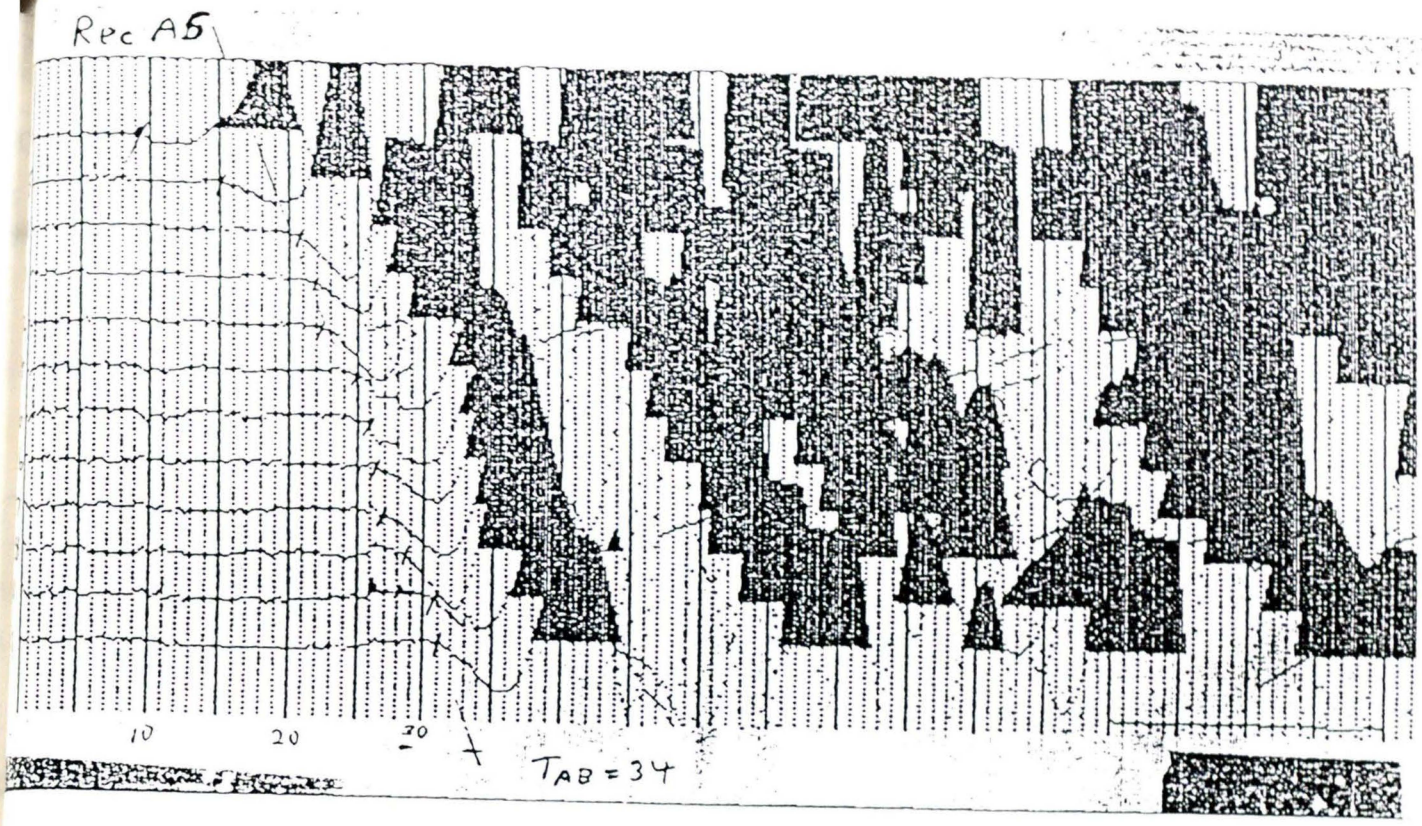
APPENDIX

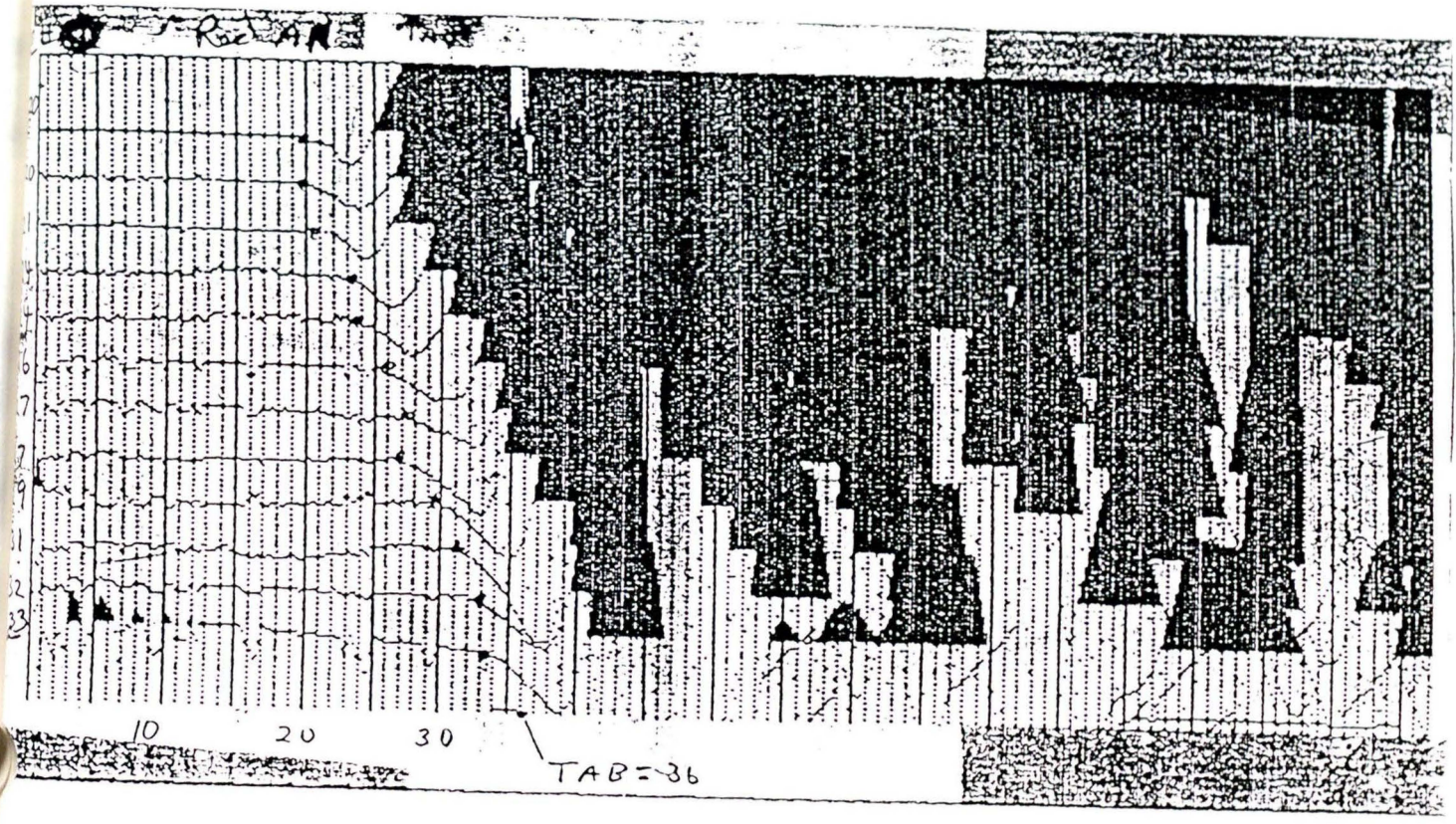
Seismic Refraction Records from the Kessler Creek Site



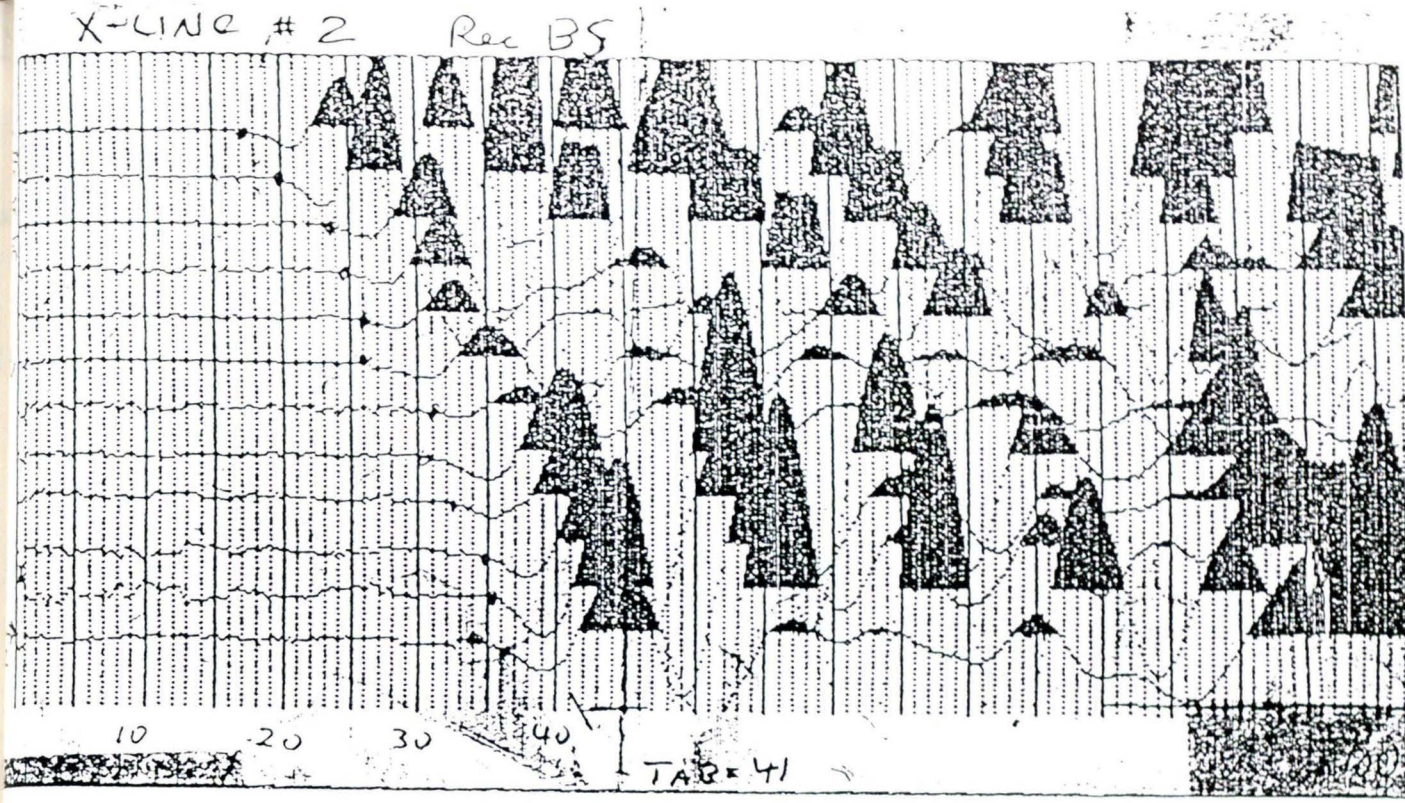


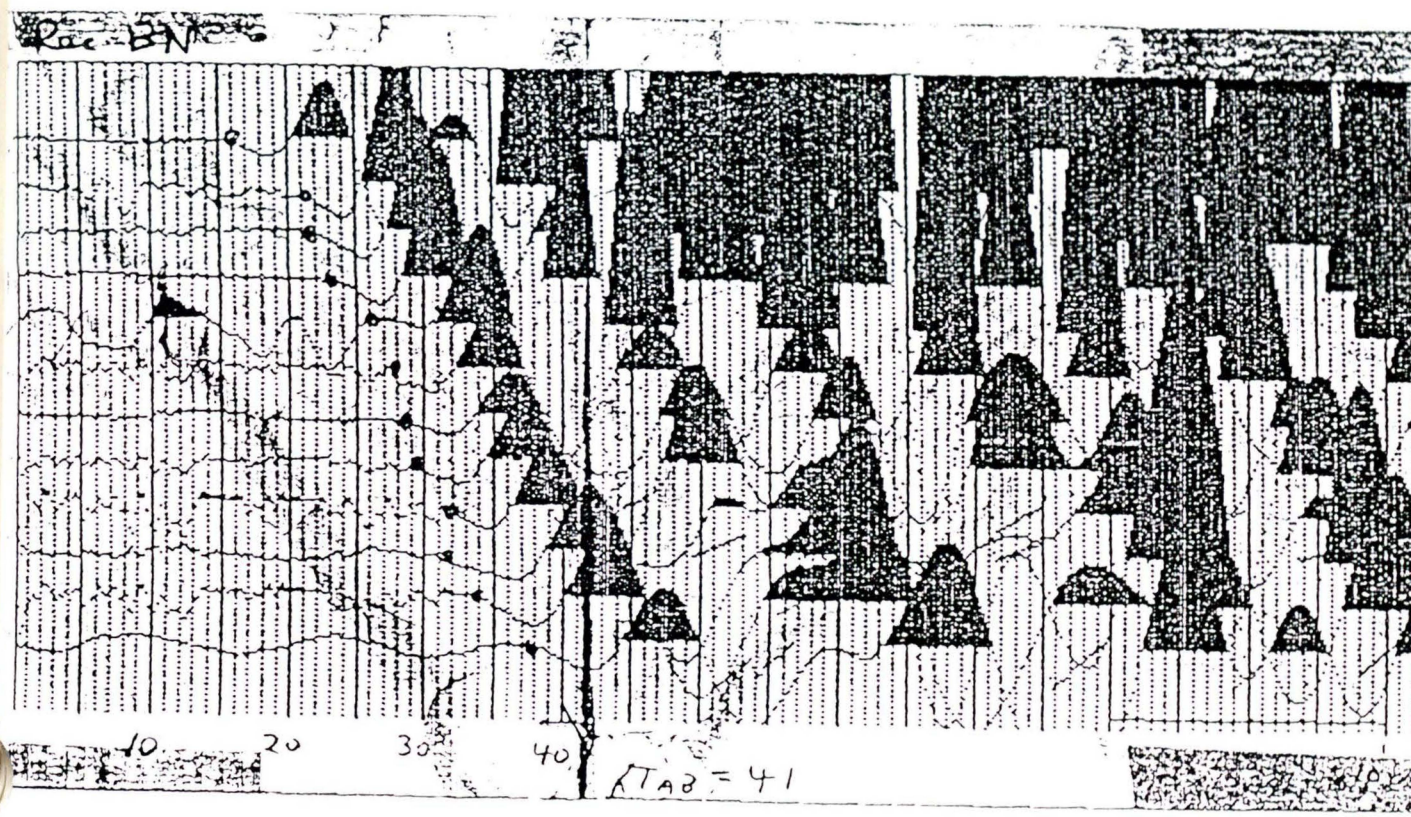
BASE LINE RECORDS



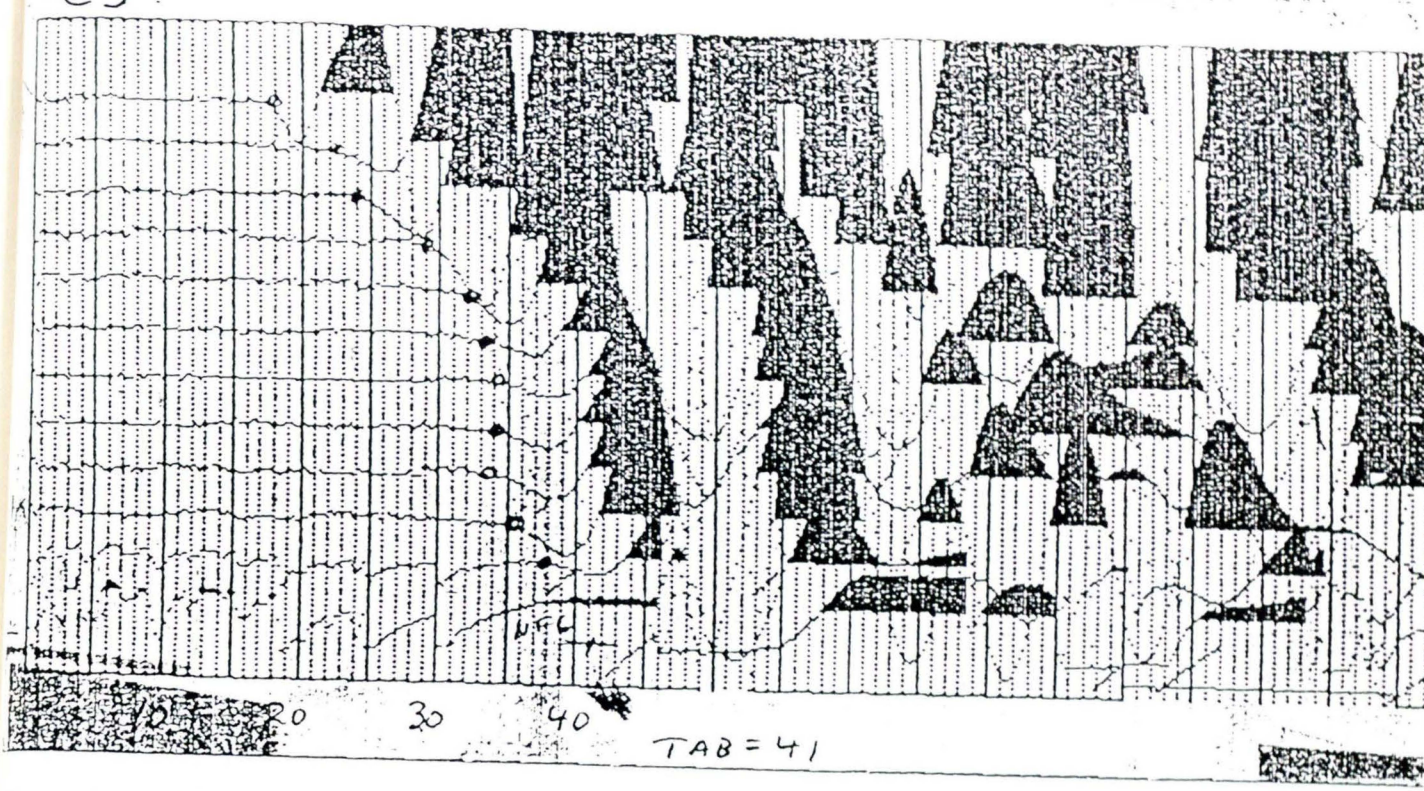


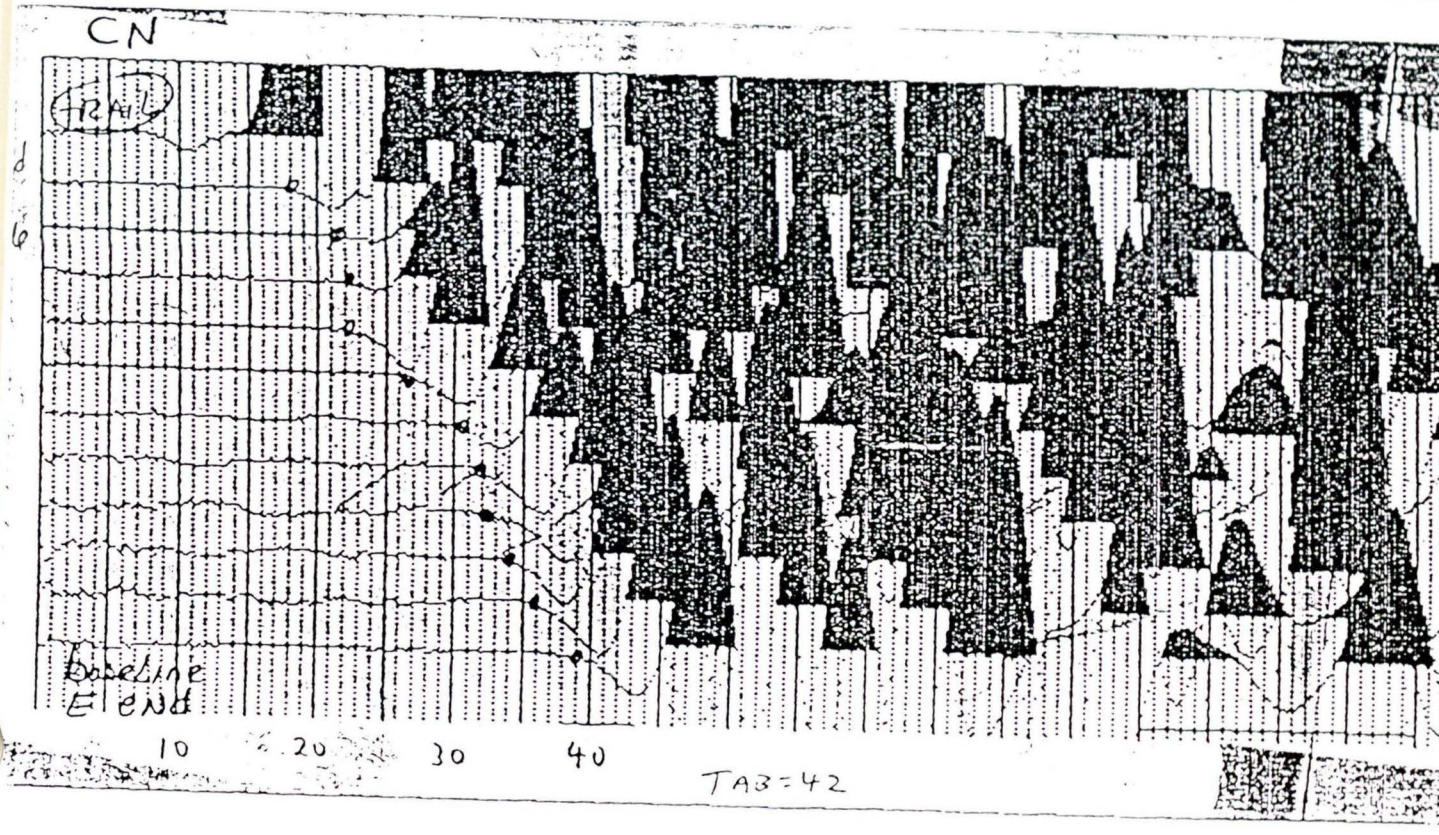
CROSS LINE #1





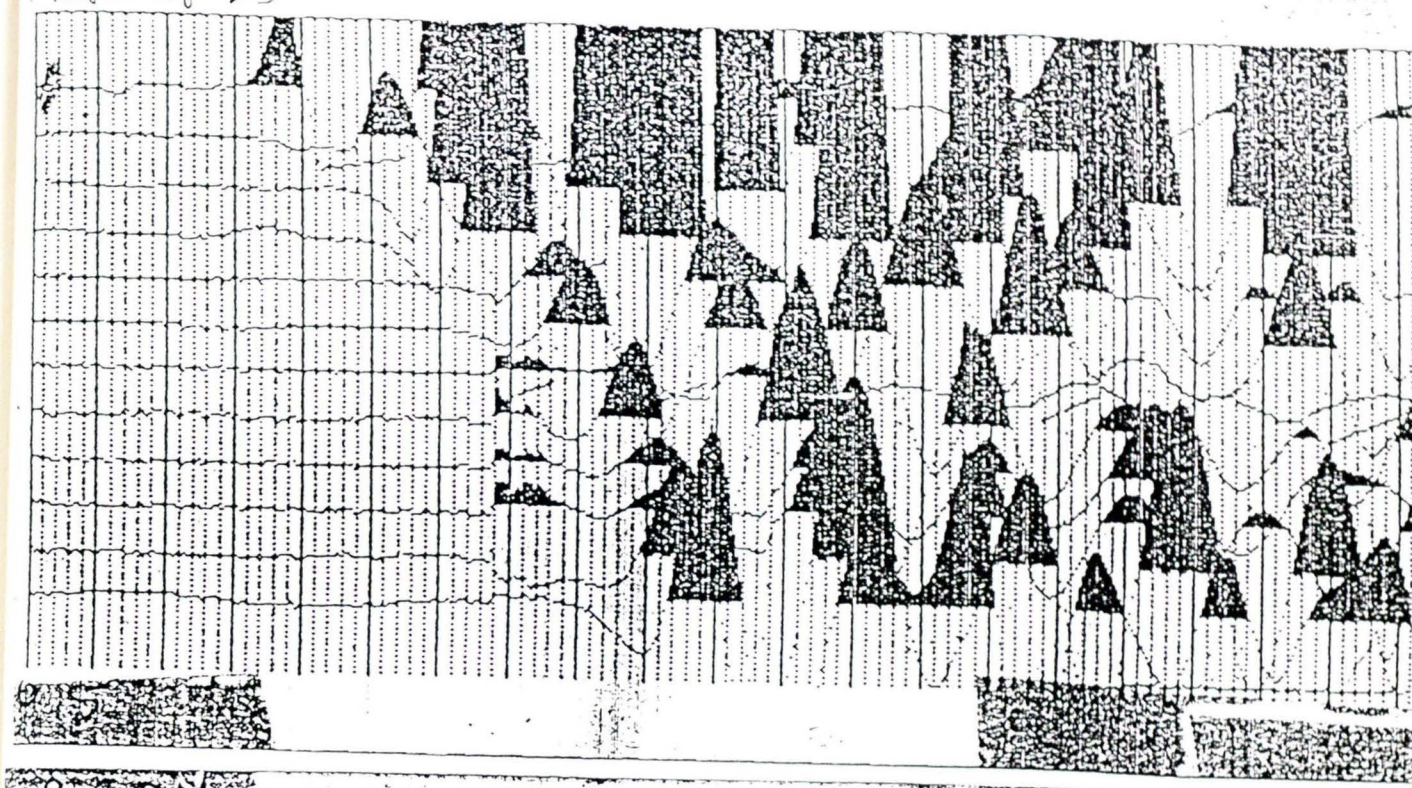
CROSS LINE #2

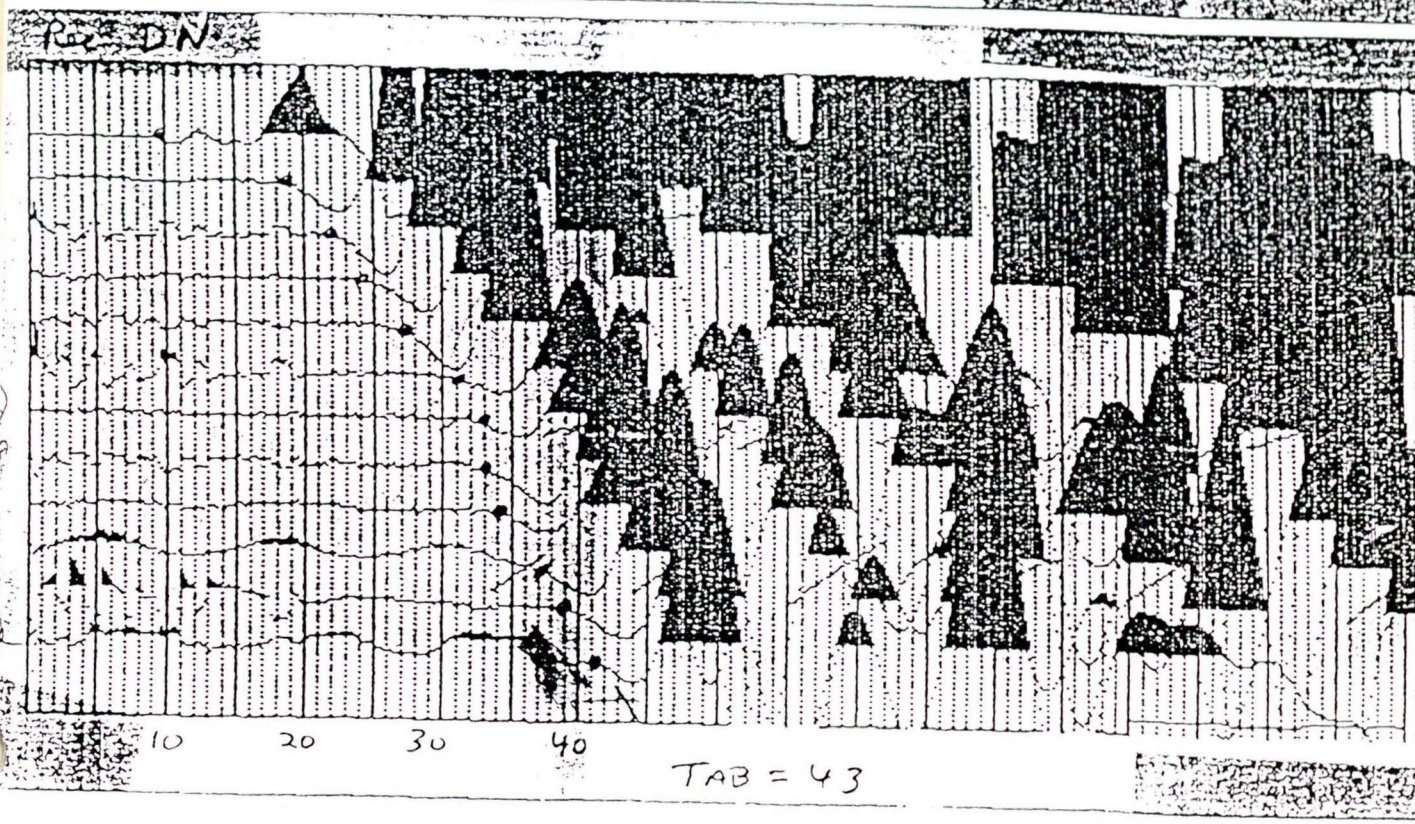




CROSS LINE #3

Portion of DS





TAB = 43

CROSS LINE #4

APPENDIX

BASIC Computer Programs

```
PRINT CHR$(27);"E"
'This program analyses seismic refraction results using the reciprocal metho
DIM DISTANCE(14),TA(14),TB(14),DEPTH(14),X(14),Y(14),MINUS(14),VELANOMALY(14
'READ RECORD ID, V1 ON FIRST DATA STATEMENT
'READ 14 DISTANCES FROM SECOND DATA STATEMENT
'READ 14 TIMES (TA) ON THIRD DATA STATEMENT IN MSEC
'READ 14 TIMES (TB) ON FOURTH DATA STATEMENT IN MSEC

READ ID$,V1
FOR I=0 TO 13:READ DISTANCE(I):NEXT
FOR I=0 TO 13:READ TA(I):TA(I)=TA(I)/1000:NEXT
FOR I=0 TO 13: READ TB(I):TB(I)=TB(I)/1000:NEXT
TAB=(TB(0)+TA(13))/2

'CALCULATE MINUS TERMS
FOR I=1 TO 12:MINUS(I)=(TA(I)-TB(I))/2:NEXT

'FIND BEST FIT SLOPE
N=12:FOR I=1 TO N:X(I)=DISTANCE(I):Y(I)=MINUS(I):NEXT:GOSUB 1000
V2=1/SLOPE
'CALCULATE PSEUDO-VELOCITY FACTOR
FACTOR=.5*V1*V2/SQR(V2*V2-V1*V1)

'CALCULATE DEPTHS AT EACH GEOPHONE
FOR I=1 TO 12:DEPTH(I)=(TA(I)+TB(I)-TAB)*FACTOR:NEXT

'CALCULATE VELOCITY ANOMALIES IN %
FOR I=2 TO 11
DELTAMINUS=MINUS(I+1)-MINUS(I-1):DELTADIST=DISTANCE(I+1)-DISTANCE(I-1)
VELOCITY=DELTADIST/DELTAMINUS:VELANOMALY(I)=(VELOCITY-V2)/V2*100
NEXT I
'PRINT OUT RESULTS
LPRINT ID$
LPRINT
LPRINT "V1 IS ";V1;"        V2 IS ";INT(V2);"        TAB IS ";TAB; "S"
LPRINT
LPRINT "DISTANCE (FT)","TA  (SEC)"," TB (SEC)","DEPTH (FT)","VEL ANOMALY %"
FOR I=0 TO 13:LPRINT DISTANCE(I),TA(I),TB(I),INT(DEPTH(I)+.5),INT(VELANOMALY
):NEXT
LPRINT:LPRINT:LPRINT:LPRINT
INPUT "PRESS <ENTER> FOR NEXT DATA SET";A$
CLS
GOTO 20
'LEAST SQUARES FIT N=#OF POINTS
SUMX=0:SUMY=0:SUMXY=0:SUMXX=0:SUMYY=0
FOR I=1 TO N
   :SUMX=SUMX+X(I):SUMY=SUMY+Y(I):SUMXY=SUMXY+X(I)*Y(I)
   :SUMXX=SUMXX+X(I)*X(I):SUMYY=SUMYY+Y(I)*Y(I)
NEXT I
SLOPE=(N*SUMXY-SUMX*SUMY)/(N*SUMXX-SUMX*SUMX)
RETURN
```

```
50 DIM X(20),Y(20),TT(20),XX(20)
100 ' This program does x2-t2 analysis
110 INPUT "NUMBER OF POINTS";N
120 FOR I=1 TO N:
130 INPUT "SHOT-RECEIVER DISTANCE";XX(I)
140 INPUT "TWO WAY TIME IN SEC"; TT(I)
150 X(I)=XX(I)*XX(I):Y(I)=TT(I)*TT(I)
160 NEXT I
170 GOSUB 1000
180 VELOCITY=1/SQR(SLOPE)
190 TIMEZERO=SQR(INTERCEPT)
200 DEPTH=VELOCITY*TIMEZERO/2
210 PRINT:PRINT:PRINT
220 PRINT "TIMEZERO=";TIMEZERO;" DEPTH=";DEPTH;"  VELOCITY=";VELOCITY
230 GOTO 110
1000 'LEAST SQUARES FIT N=#OF POINTS
1010 SUMX=0:SUMY=0:SUMXY=0:SUMXX=0:SUMYY=0
1020 FOR I=1 TO N
1030    :SUMX=SUMX+X(I):SUMY=SUMY+Y(I):SUMXY=SUMXY+X(I)*Y(I)
1040    :SUMXX=SUMXX+X(I)*X(I):SUMYY=SUMYY+Y(I)*Y(I)
1050 NEXT I
1060 SLOPE=(N*SUMXY-SUMX*SUMY)/(N*SUMXX-SUMX*SUMX)
1065 INTERCEPT=(SUMY*SUMXX-SUMX*SUMXY)/(N*SUMXX-SUMX*SUMX)
1070 RETURN
```

APPENDIX

Seismic Refraction Results

BASELINE

V1 IS 1390 V2 IS 6008 TAB IS .044 S

DISTANCE (FT)	TA (SEC)	TB (SEC)	DEPTH (FT)	VEL ANOMALY
0	0	.044	0	0
20	.027	.039	16	0
30	.028	.038	16	-34
40	.03	.032	13	-27
50	.031	.032	14	-5
60	.032	.027	11	10
70	.033	.028	12	66
80	.034	.025	11	-5
90	.036	.024	11	66
100	.035	.022	9	33
110	.036	.019	8	-40
120	.04	.016	9	-27
130	.041	.015	9	0
150	.044	0	0	0

CROSS LINE #1

V1 IS 1390 V2 IS 8849 TAB IS .035 S

DISTANCE (FT)	TA (SEC)	TB (SEC)	DEPTH (FT)	VEL ANOMALY
0	0	.034	0	0
25.5	.02	.031	11	0
36.5	.02	.031	11	24
47.5	.021	.028	10	-38
58.5	.024	.027	11	-1
69.5	.024	.026	11	65
80.5	.026	.026	12	-1
91.5	.027	.024	11	-1
102.5	.027	.022	10	-1
113.5	.029	.021	11	-1
124.5	.031	.021	12	-1
135.5	.032	.019	11	-18
146.5	.033	.017	11	0
159.5	.036	0	0	0

CROSS LINE #2

V1 IS 1390 V2 IS 7875 TAB IS .041 S

DISTANCE (FT)	TA (SEC)	TB (SEC)	DEPTH (FT)	VEL ANOMALY
0	0	.041	0	0
20	.016	.034	6	0
33	.021	.035	11	65
46	.021	.035	11	32
59	.023	.032	10	-34
72	.026	.03	11	10
85	.028	.031	13	-10
97	.029	.026	10	5
110	.029	.026	10	65
123	.032	.025	11	65
136	.031	.024	10	-6
149	.034	.02	9	-53
162	.038	.017	10	0
182	.041	0	0	0

GROSS LINE #3

V1 IS 1390 V2 IS 8255 TAB IS .0415 S

DISTANCE (FT)	TA (SEC)	TB (SEC)	DEPTH (FT)	VEL ANOMALY
0	0	.041	0	0
10	.016	.039	10	0
25.5	.018	.038	10	-17
41	.021	.035	10	-7
56.5	.022	.034	10	275
72	.022	.034	10	87
87.5	.026	.034	13	-17
103	.03	.033	15	-7
118.5	.032	.032	16	25
134	.032	.029	14	-25
149.5	.034	.024	12	-32
165	.036	.022	12	-32
180.5	.039	.018	11	0
200.5	.042	0	0	0

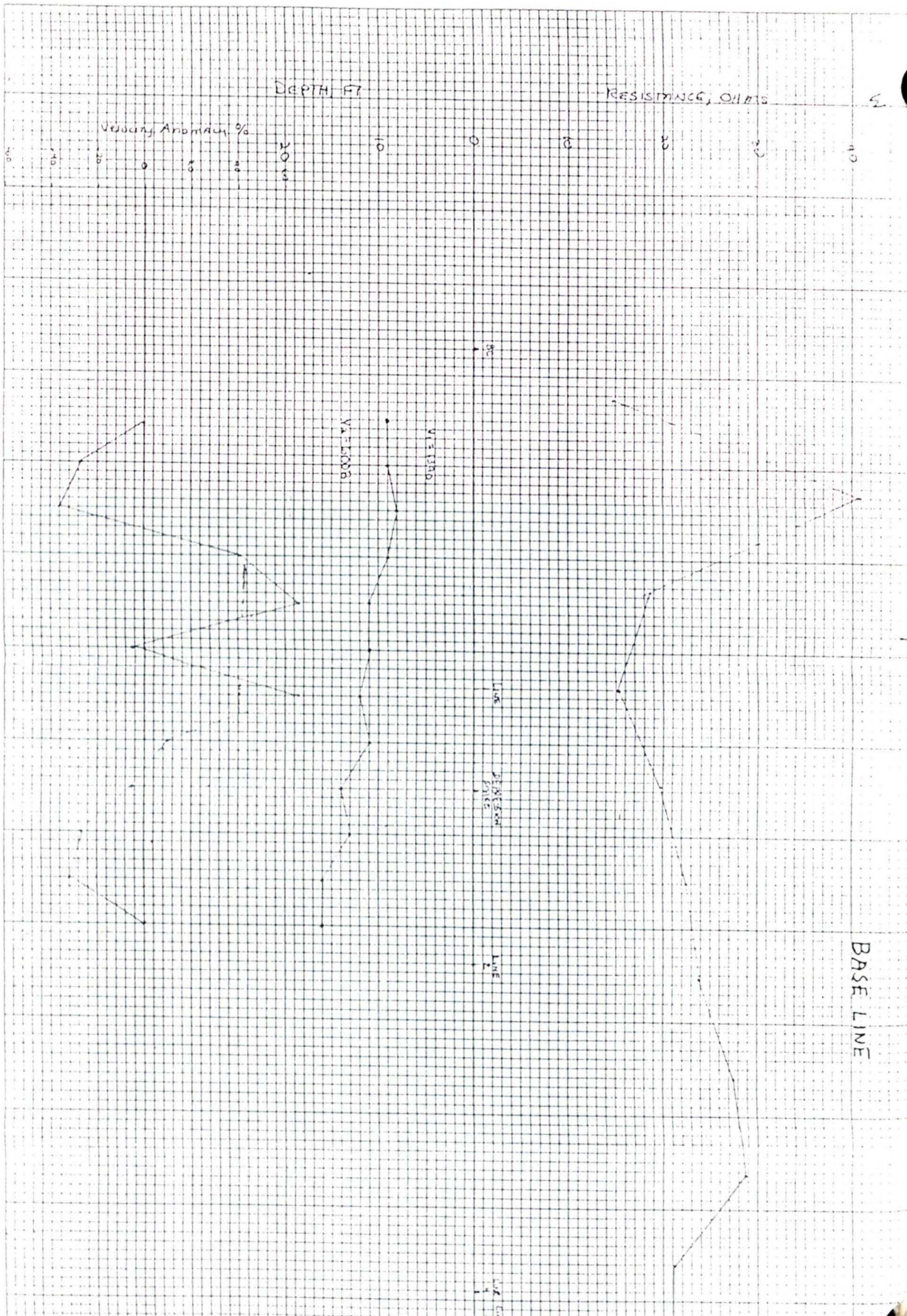
CROSS LINE 4

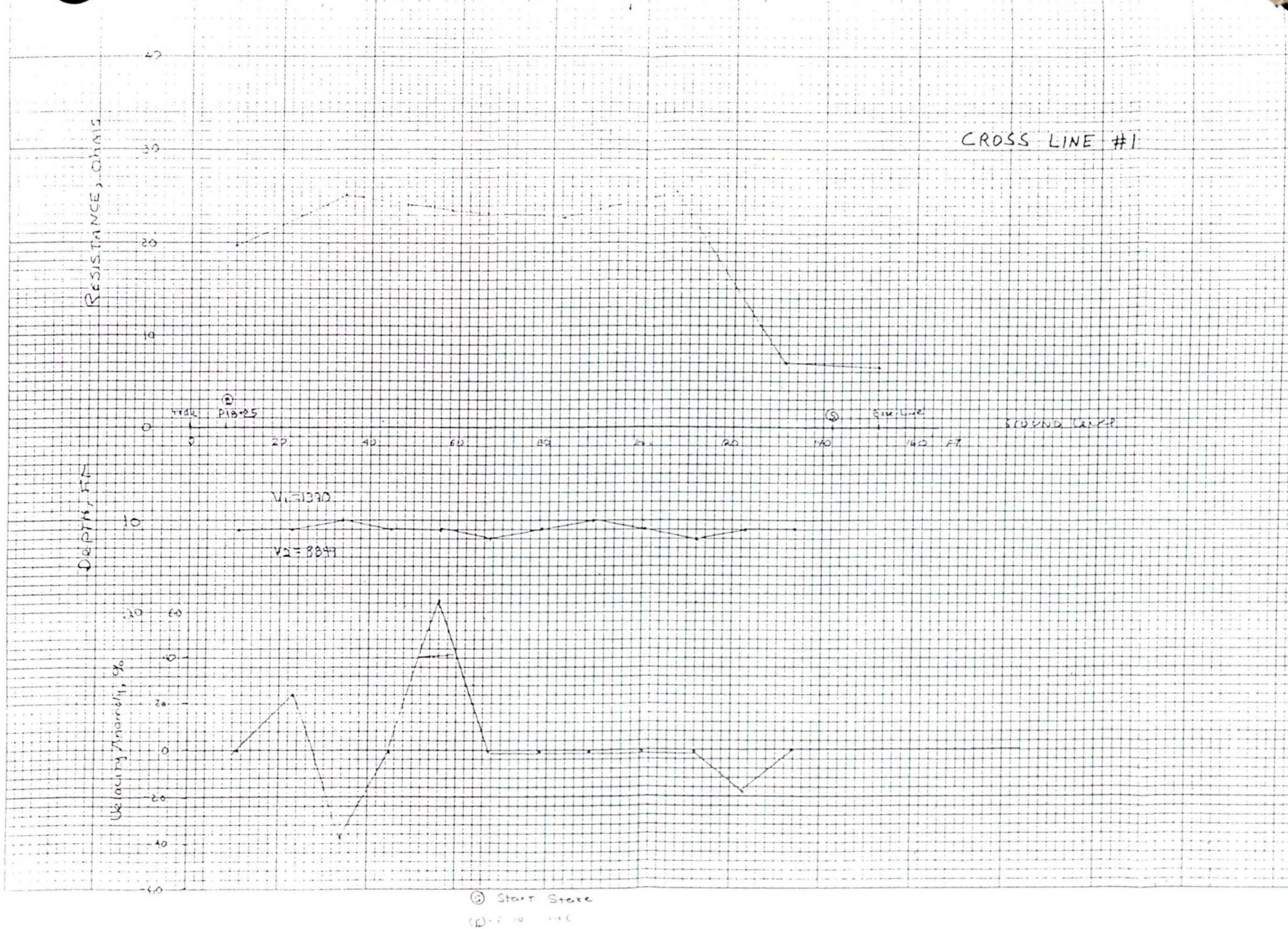
V1 IS 1390 V2 IS 6662 TAB IS .043 S

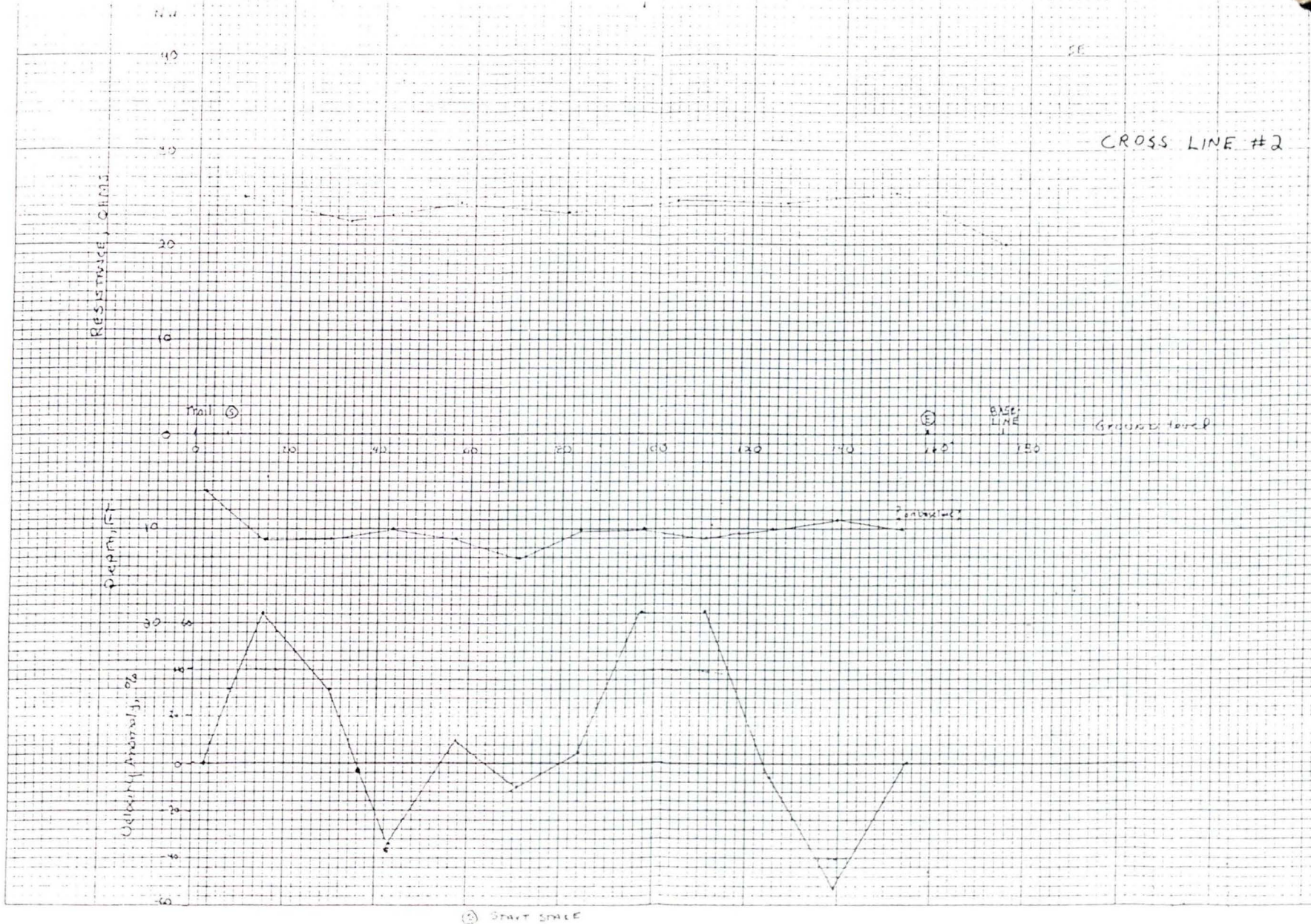
DISTANCE (FT)	TA (SEC)	TB (SEC)	DEPTH (FT)	VEL ANOMALY
0	0	.043	0	0
12.5	.016	.04	9	0
26.5	.019	.038	10	-7
40.5	.022	.037	11	20
54.5	.024	.036	12	20
68.5	.027	.035	14	5
82.5	.031	.035	16	-24
96.5	.033	.03	14	-7
110.5	.033	.028	13	20
124.5	.034	.024	11	5
138.5	.037	.024	13	5
152.5	.039	.021	12	-16
166.5	.041	.018	11	0
176.5	.043	0	0	0

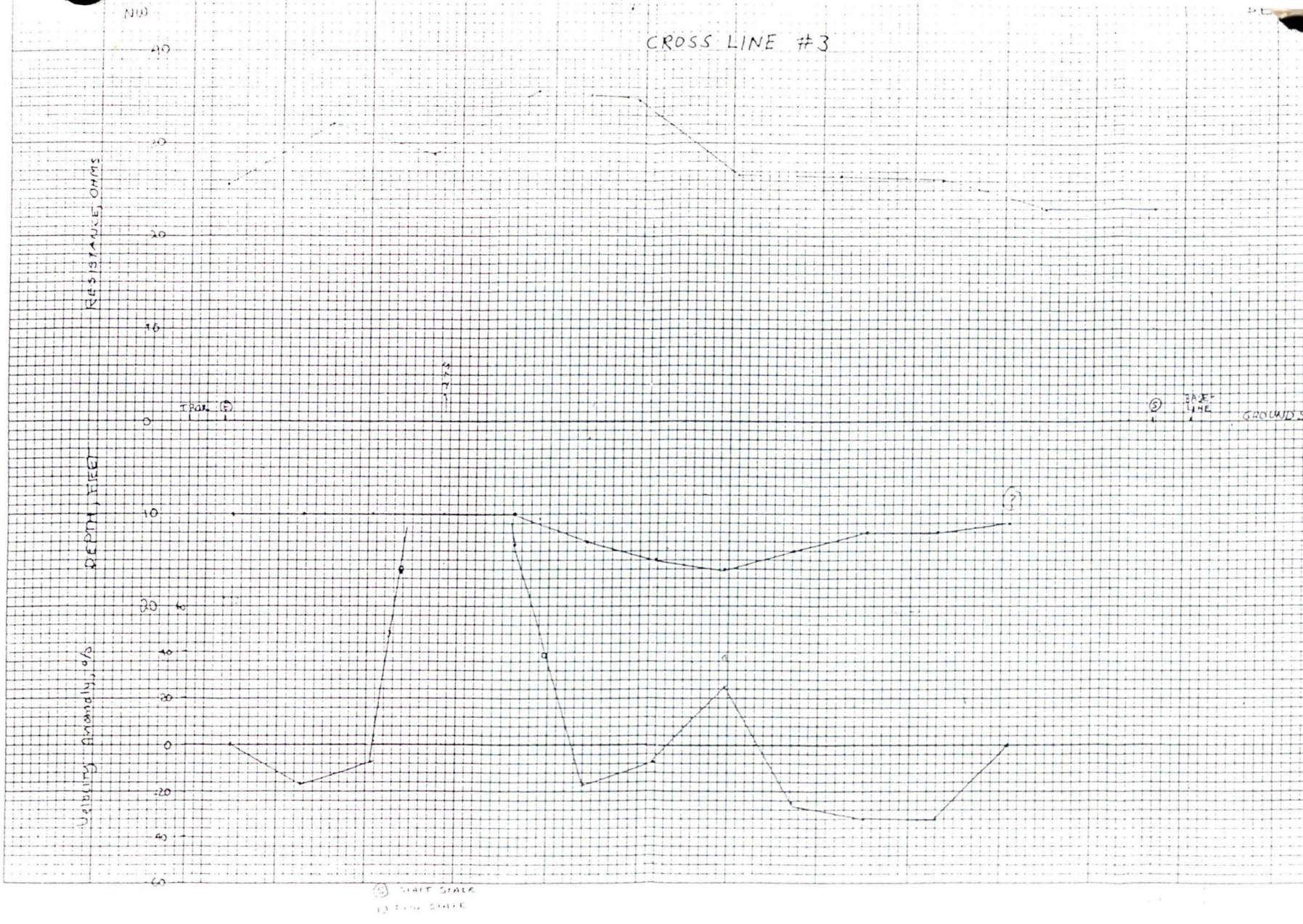
APPENDIX

Profiles of Seismic and Resistivity Results


DEPTH FT
RESISTANCE, OHMS
Vertical Anomaly %
VALLEY
VALLEY
BASE LINE


CROSS LINE #1
RESISTANCE, OHMS
DEPTH, FT.
V1=1030
V2=8047
Velocity, ft/sec
Start Stake
FEET
GROUND LEVEL

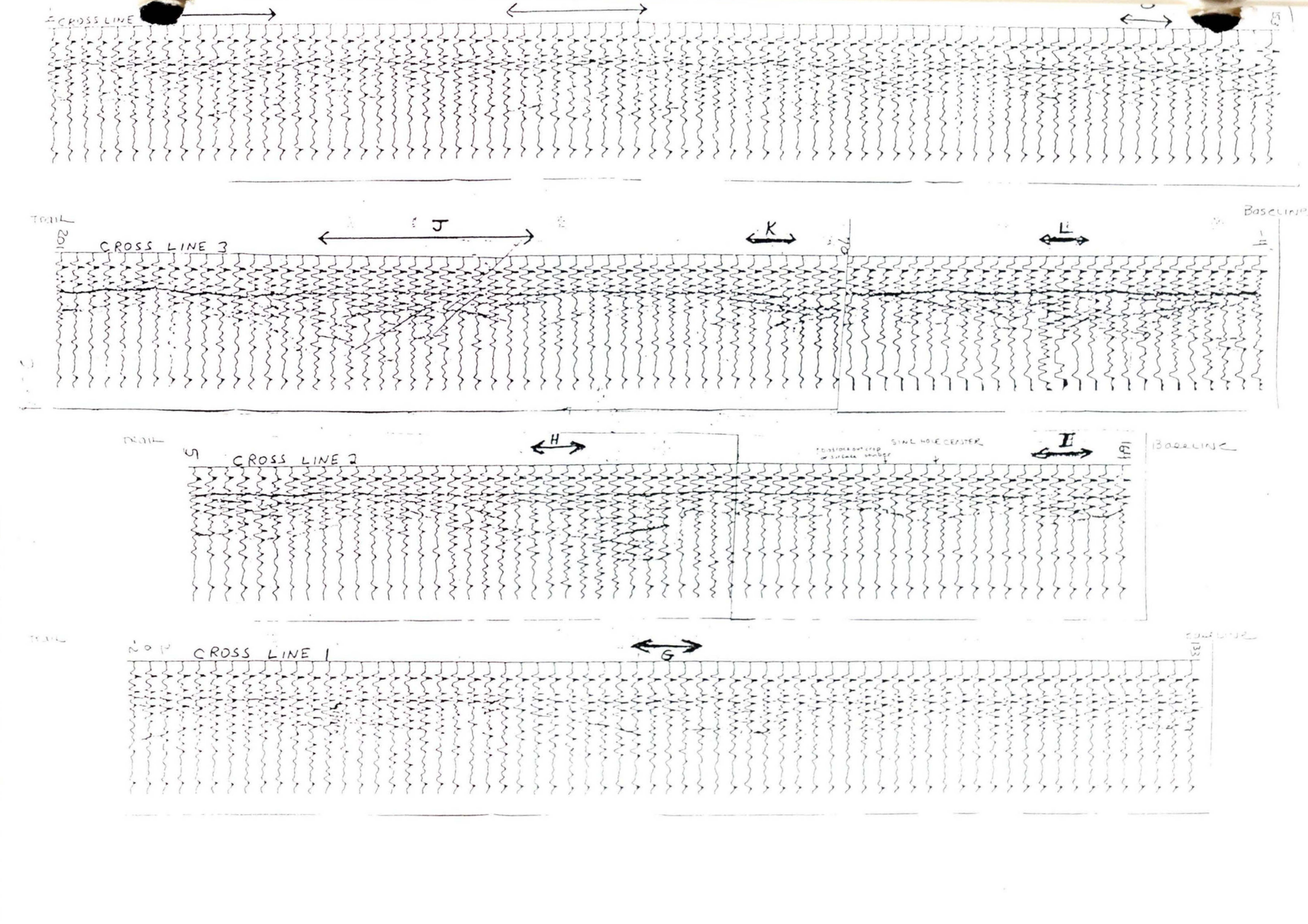

CROSS LINE #2
RESISTIVITY OHMS
DEPTH FEET
Trail ⑤
BASE LINE
Ground level
Contours
Ground level
⑤ START SPACE

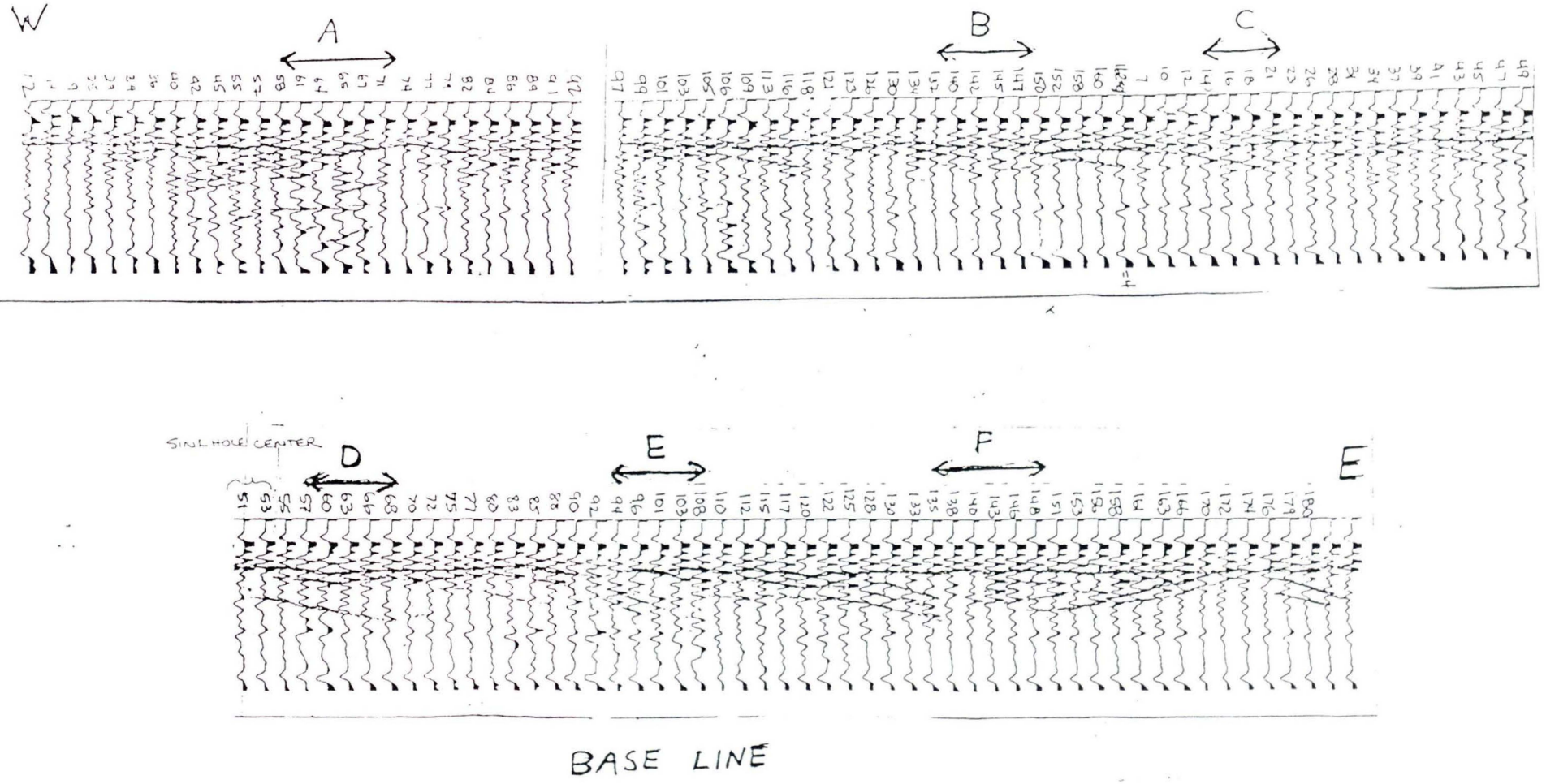

CROSS LINE #3
RESISTANCE, OHMS
DEPTH, FEET
Usibility Anomaly, o/s
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
340
350
360
370
380
390

CROSS LINE #4
DEPTH, FT
RESISTANCE, OHMS
Tail
Base Line
Vmax
Vmin

APPENDIX

Continuous Ground-Probing Radar Profiles


CROSS LINE
CROSS LINE 3
J
K
L
Baseline
CROSS LINE 2
H
I
Baseline
CROSS LINE 1
G


W
A
B
C
SINK HOLE CENTER
D
E
F
E
BASE LINE

THESIS/
REPORTS
SPRENKE,
K.F.

USDA FOREST SERVICE

and

THE UNIVERSITY OF IDAHO

Intermountain Forest and Range Experiment Station

Cooperative Project

Final Report

Cooperative Agreement No. 22-C-4-INT-165

Problem 3 (14), Study #6, Subproblem C

Fiscal Years 1983-1986

Geophysical Methods for Determining Soil Thickness and Bedrock Configuration

Prepared by .....Date:.....

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